STATUS OF THE EUROPEAN XFEL

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Abstract

The European XFEL is one of the world's largest accelerators presently under construction. The facility includes a 17.5 GeV superconducting linac with more than 3 km of electron beam transport lines and up to 5 FEL undulators [1]. In mid-2013 the underground civil construction will finish. With most of the large scale production ramping up and first accelerator components installed, this paper presents the XFEL facility status and plans for accelerator commissioning including prospects for first XFEL experiments in Hamburg.

INTRODUCTION

The European XFEL will provide hard and soft X-rays for a wide range of scientific applications. In its initial stage it will host three independent photon beam lines serving two experiments each. In a later stage the number of photon beam lines can be extended to five, and the number of experiments per beam line to three.

The European XFEL employs superconducting RF technology, leading to unique features compared to other X-ray FELs being constructed or in operation worldwide. It is capable of accelerating up to 27,000 bunches per second, distributed into 10 pulses of 600 µs length. Bunches can be injected into two separate electron beam lines hosting two resp. up to three undulators in a row. Flexible bunch patterns and plans to provide individual bunch properties will make the European XFEL a true multi-user facility.

The main parameters of the European XFEL are summarized in Table 1. The final energy of 17.5 GeV, together with the long undulators and the anticipated low emittance beams out of a photo cathode gun will allow reaching photon wavelengths as short as 0.5 nm [2].

The installed linac and its infrastructure bear the possibility to be converted into a CW (or quasi-CW) accelerator in the future with the potential to reach up to 6 GeV final energy (for an update in the R&D towards this option see [3]).

A normal-conducting photo-cathode RF gun produces high brightness electron beams. One accelerator module with eight 1.3 GHz cavities, a 3rd harmonic module with eight 3.9 GHz cavities, a laser-heater, and a section for longitudinal and transversal beam diagnostics serve to complete the injector linac. The injector building allows for the later installation of a second, completely independent injector. Until then the space may be used for a gun test stand for conditioning spare guns.

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The main linear accelerator is sectioned into three units with 4, 12 and 84 modules each, intercepted by normal-conducting bunch compressor and diagnostic sections. At the end of the main tunnel and inside the first separation shaft a collimation and beam distribution section follows the linac. Here the beam can either be led into a beam dump or fed into two separate undulator beam lines. The former option applies for commissioning purposes as well as for spare pulses that are kicked out of the bunch train to allow for the generation of flexible pulse patterns without disturbing the main linac RF control. Each beam line is terminated by a solid state beam dump capable of accepting up to 300 kW of continuous beam power. The SASE photon beam is delivered through up to 800 m long photon beam lines into the experimental hall. See Figure 1 for a bird's eye view of the facility.

Table 1: European XFEL Parameters

Quantity	Value
Electron energy	10.5/14/17.5 GeV
Macro pulse repetition rate	10 Hz
RF pulse length (flat top)	600 µs
Bunch repetition frequency within pulse	4.5 MHz
Bunch charge	0.02 - 1 nC
Electron bunch length after compression (FWHM)	2 - 180 fs
Slice emittance	0.4 – 1.0 mm mrad
Beam power	500 kW
# of modules containing eight 9-cell superconducting 1.3 GHz cavities	101
Accelerating gradient for 17.5 GeV	23.6 MV/m
# of 10 MW multi beam klystrons	27
Average klystron power for 0.03 mA beam current at 17.5 GeV	5.2 MW
Photon wavelength	0.05 – 4 nm

INSTALLATION STATUS

Civil Construction

The European XFEL requires a large amount of civil construction at three construction sites as can be seen in the figure 1. On the DESY campus (DESY Bahrenfeld) the injector building, modulator hall and accelerator module test facility (AMTF), on the future XFEL

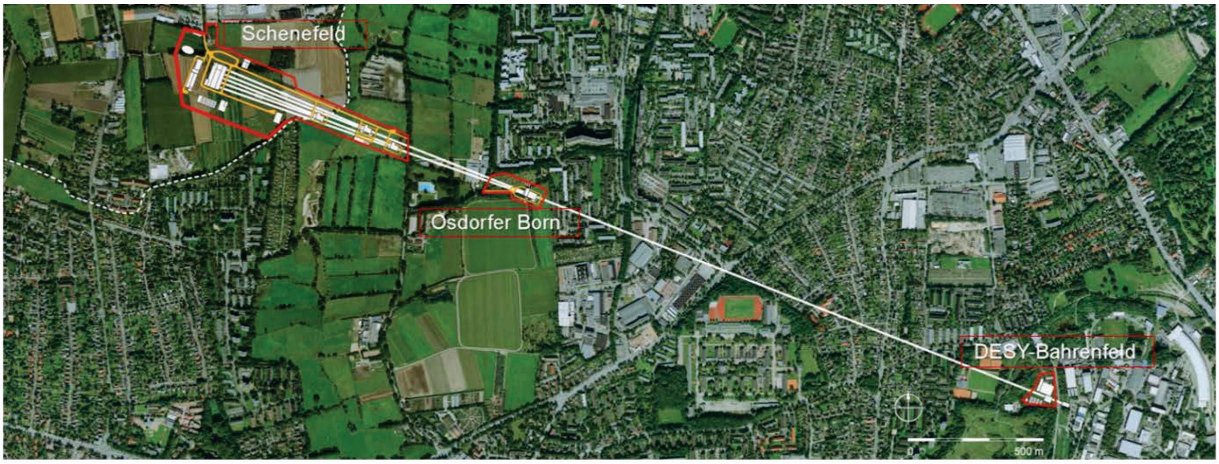

Figure 1: Bird's eye view of the European XFEL site showing the location of the three surface areas and the tunnel routing below the cities of Hamburg and Schenefeld.

experimental campus (Schenefeld) the large experimental hall, tunnel separation shafts, dump shafts, office buildings and infrastructure buildings, and a tunnel separation shaft and surface infrastructure building at the end of the main accelerator tunnel (Osdorfer Born). The whole accelerator and FEL complex spans 3.4 km to the west of the DESY campus, consisting of 5.8 km of underground tunnels and shafts. Two tunnel boring machines were deployed, one providing a tunnel diameter of 5.3 m for the main accelerator and first undulator tunnels and one for a tunnel diameter of 4.6 m in the photon tunnels. The major part of the main accelerator tunnel crosses residential and commercial area.

Civil construction started in 2009 and is nearing completion. Tunnelling work commenced in June 2012 when the last photon tunnel was completed, the main accelerator tunnel was handed over from the civil construction contractor to the European XFEL in February 2012. The last of the photon tunnels and the remaining part of the underground experimental hall are scheduled to be handed over in June 2013.

The buildings above surface on the DESY Bahrenfeld campus have been handed over already. The shaft entrance building on the Osdorfer Born site will be handed over in July 2013, those on the Schenefeld campus before end of 2013. Civil construction of the main office and lab building of the European XFEL on top of the experimental hall is scheduled to be completed in September 2014.

Infrastructure Installation

Installation of the technical infrastructure in the buildings is scheduled and contracted separately from the civil construction. In most cases it directly follows the availability of the respective tunnel section or building, except for parts of the undulator and photon distribution fan where the infrastructure installation was spread over a longer time span to account for the limited capacity for ordering and supervising the work. In the main accelerator tunnel (XTL, see figure 2) the tasks are dominated by the cabling work underneath the tunnel floor. To allow for work under the floor it is made up from 400 concrete plates resting at four points on a concrete frame. This results in unsteady positioning of the plates which is compensated in two ways. First, on the transport path the rubber dampers known from urban railways are placed under the plates to avoid long-ranging low frequency noise. Second, under the normal-conducting parts of the machine the plates are bedded into a layer of epoxy glue whose height exactly adjusts to the unevenness of the plates. The latter solution is pending confirmation.

Figure 2: View of the main accelerator tunnel against the direction of the beam. On the right the cable trays are visible which will be hidden under the floor during operation.

Infrastructure installation in the injector complex is scheduled to be finished in June 2013. Specific areas of the building were given priority and are handed over earlier to allow for earlier installation of machine equipment.

Following the handover (July 2013) of the entrance building to the first separation shaft on the Osdorfer Born site the infrastructure installation continues in one of the

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two undulator tunnels. Installation in the second undulator tunnel however will be delayed until after the experimental hall is nearly finished so that commissioning in the first beam line can early. The distribution fan is set up such that installation work can continue in one stretch of beam line while the other is already taking beam.

Machine Installation

Machine installation starts in the injector with the RF gun. It will be tested in its final configuration before the installation work continues for the rest of the injector linac. The injector is located in an enclosure which can be closed and operated independently from installation work in the main linac tunnel.

Machine installation in the main tunnel starts in the fall of 2013 with the installation of the first string of accelerator modules. It is foreseen to start installation with the shortest string consisting only of 4 modules which also is the size of one RF string. This allows for an early start of installation work with a buffer for training on the first installation. The following modules have to be installed in groups of twelve. The installation and manufacturing schedules of all other components in the main linac section are adjusted such that the duration and finishing time of the main linac installation are dominated by availability of accelerator modules, which are the core items and the most difficult to obtain. The module fabrication is handled in another section. The overall goal however is to maintain that the machine installation is finished and the accelerator tunnel closed before end of 2015.

In the SASE sections the distinction is not as obvious because the undulators, the undulator vacuum chamber and the intersections are equally important and critical.

MANUFACTURING STATUS

Cavities

Manufacturing of the 800 superconducting cavities is completely done by industry. The order has been split into two lots contracted to two vendors. The performance goal is an acceleration gradient of 23.6 MV/m at $Q_0=1\cdot 10^{10}$. The risk of performance failure however is not taken by the vendors but by DESY. Should a cavity fall short of this goal, it is re-treated by DESY (Supported by the EU-CRISP program [7]). Both vendors were qualified for mechanical fabrication of niobium cavities, but the further processing of the cavities in the past was done by DESY. For qualification of the individual processing steps reference cavities were treated at the companies and tested at DESY after each step. By end of February 2013 both vendors were fully qualified for the processing of cavities.

Meanwhile more than 100 cavities have been mechanically produced by the two vendors. As of May 7th the first 22 series cavities were tested at DESY, most of them in the newly built cavity and module testing facility AMTF (see figure 3). Out of these 22 cavities 19 reached the performance goal in the first test, many of them exceeding it by a big margin, and 3 were re-treated and reached the goal in the second test. Detailed results will be published elsewhere as soon as a larger sample provides better statistics [6].

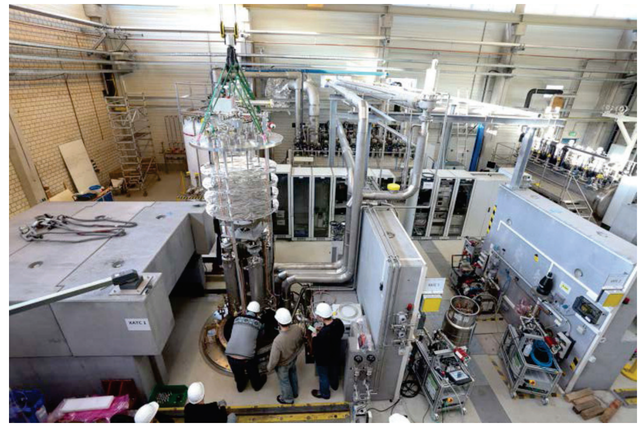

Figure 3: Vertical test cryostat at the accelerator module test facility (AMTF) while a set of 4 cavities is lowered into the cryostat for acceptance test.

Accelerator Modules

The module assembly integrates the individual parts of the superconducting module. The major parts besides the cavities are the power couplers, the cavity tuners, cold vacuum pieces, the cold quadrupole package, beam position monitor and the cold mass. Among these items the power couplers turned out to be the limiting ones. This is due to technical challenges during copper plating of the coupler parts. Meanwhile the fundamental problems have been resolved. The results of layer thickness and residual resistance ratio (RRR) are merely slightly out of tolerance and expected to fulfil the specifications soon. The remaining problem is the yield of the plating process limiting the overall production rate. For further details see [4].

The module assembly of the series production modules has not started yet. In the moment the training of the assembly teams is proceeding with three pre-series modules. The assembly of the first series module can start in summer 2013. After a ramp-up phase originally a production rate of one module per week was aimed for. When a steady production rate is achieved it will be carefully assessed in view of the goal of closing the main tunnel before end of 2015.

The module test stands in the AMTF are nearing completion and soon will be ready for operation. Three individual test stands allow a through-put of more than one module per week. The testing procedure takes about two weeks for each module. In addition before the test the modules are equipped with patch panels, cable trays and cables to the coupler ports before the test, which are calibrated and quality checked before and during the test. This reduces the risk of malfunctioning of the cable connections and damage to the coupler port during installation. After the test the waveguide distribution is

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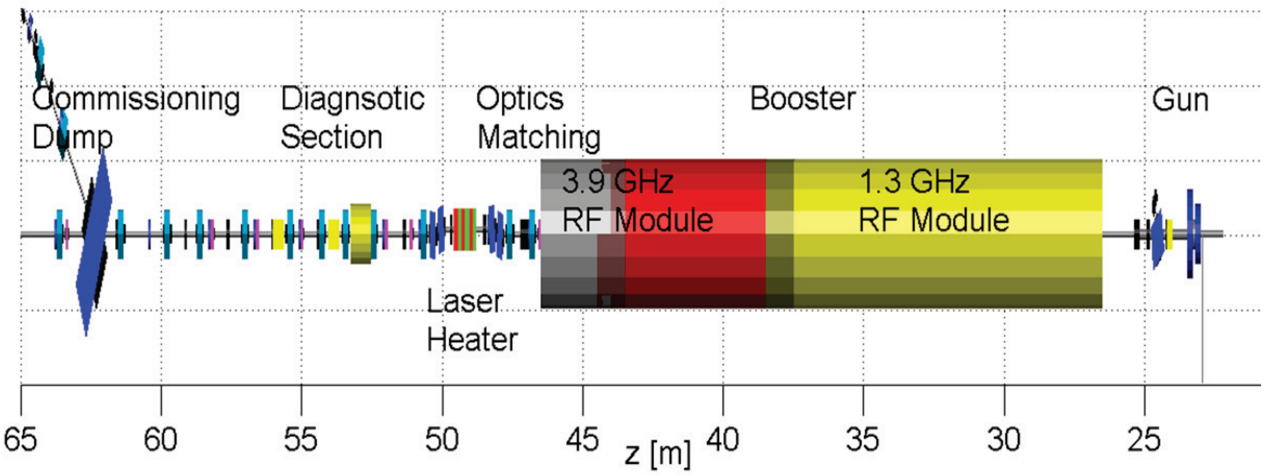

Figure 4: Sketch of the injector linac with the key components. The injector linac contains almost all elements that are found in the main linac as well.

tailored to the module performance and attached. This increases the working time for the individual module but does not affect the through-put.

Undulator Systems

The undulator system consists of 5 m long undulator segments, intersections of 1.1 m, the vacuum chamber with support system and the control rack. For the three SASE sections 70 undulators with a period of 40 mm and 21 undulators with a period of 68 mm are required. The series production of undulator segments started in October 2012 and is scheduled to finish by end of 2014. The mounting of the magnetic structure, the magnetic measurements, the tuning and the preparations for installation take three weeks. To achieve the required output rate it was necessary to set up three assembly lines including three magnetic labs with strict requirements on air conditioning.

As of April 19^{th} a total of 43 support systems and 38 magnet structures have been delivered, 22 undulator segments have been measured and tuned, 18 segments are ready for installation.

The undulator intersection consists of a phase shifter, a quadrupole mounted on a 2D mover, a high precision re-entrant cavity BPM and air coil correctors. The parts for the intersections are in production, assembly will start early 2014.

Other Systems

Manufacturing of the main beam dumps has started. The procurement of the system was transferred from the in-kind partner to DESY. The resulting delay consumed all contingency in the manufacturing schedule, which was considered indispensable for such a crucial device.

For the same reason the delivery of the cryogenic transfer line from the cryogenic plant to the accelerator facility, the feed-caps, the end-caps, the string-connection boxes and the bypass lines for the warm beam lines are delayed, too. Among these the delay of the main transfer line is the most critical because it affects the cool-down of the injector linac.

Manufacturing of electronic components is in full swing for most systems, E.G. the door interlocks, the diagnostic systems and the RF control (LLRF). Prototypes of the LLRF system are tested extensively and very successfully at FLASH [5].

Delivery of klystrons, modulators and pulse transformers has started. The first modulators were installed in the modulator hall nearby the injector complex. The installation of the pulse cables that connect the modulators with the pulse transformers in the main accelerator tunnel is nearly finished.

COMMISSIONING

Beam commissioning of the European XFEL will start with a thorough commissioning of the injector linac. The injector can be operated independently of installation work in the main tunnel. The injector contains all major systems also present in the main linac (see figure 4). Therefore it is expected that operation time spent on the injector saves debugging time during commissioning of the main linac. It is estimated that 10 months are required to bring the injector to its full operation parameters. In addition 2 months of contingency are foreseen. Therefore it is envisaged to start the injector operation by beginning of 2015. This is in line with the availability of the cryogenic supply.

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The first operation of the main linac will be done with a reduced parameter set. The beam energy will fixed to the maximum working point, the bunch repetition rate to 100 kHz, the bunch charge to 0.5 nC, and the bunch length to 90 fs.

The optimum strategy for the machine commissioning calls for sequentially commissioning of the accelerator sections; only proceeding to the next section after all subsystems are completely functional up to that respective point. To allow for an early commissioning of the undulator and photon systems however a fast track in the schedule towards beam delivery for the SASE beam lines has been identified. In this way first beam in the SASE1/3 beam line is expected 2 months after start-up of the main linac and first lasing 2 months thereafter. This is achieved with sacrificing thorough commissioning of the upstream sections. This has to be made up for later by parallel commissioning of the accelerator and photon systems. The first user experiments can be expected earliest 10 months after the initial start-up of the main linac with the reduced parameter set.

SUMMARY

Construction of the European XFEL is well under way with the goal of closing the accelerator tunnel in 2015. All underground buildings and tunnels are completed or nearing completion. The first surface buildings are finished and erection of remaining ones is well under way. Infrastructure installation is in full swing and close to completion in several sections of the machine. The delivery of accelerator components has started. Timely production of 101 superconducting accelerator modules remains one of the biggest challenges. The ramping up of production takes longer than anticipated and it is still unclear when the full production rate is reached.

Commissioning of the European XFEL starts with the injector one year prior to the main linac. Beam operation in the main linac can be expected beginning of 2016. Currently the commissioning plans foresee early injection into the SASE beam-lines to allow for parallel commissioning of accelerator and photon systems.

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