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The European XFEL—Status and commissioning*†

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Abstract
The European XFEL under construction in Hamburg, Northern Germany, aims to produce X-rays in the range 260 eV to 24 keV using three undulators that can be operated simultaneously with up to 27,000 pulses per second. The FEL is driven by a 17.5 GeV superconducting linac. Installation of this linac is now finished and commissioning will take place next. First lasing is expected for spring 2017. This paper summarizes the status of the project. First results of the injector commissioning are given.

Keywords
European XFEL; superconducting linac; long bunch trains.

1 Introduction

The accelerator complex of the European XFEL [1] is being constructed by an international consortium under the leadership of DESY. Seventeen European research institutes contribute to the accelerator complex and to the comprehensive infrastructure. Major contributions are coming from Russian institutes. DESY co-ordinates the European XFEL Accelerator Consortium but also contributes with many accelerator components and the technical equipment of buildings, with associated general infrastructure. With the finishing of accelerator installation, the commissioning phase is now starting, with cool-down of the main linac scheduled for the end of November 2016.

2 Layout of the European XFEL

In the following, an overall layout of the European XFEL is given, with emphasis on the different sections of the accelerator complex.

2.1 Introduction to the accelerator

The European XFEL, with its total facility length of 3.4 km, follows the established layout of a high-performance single-pass self-amplified spontaneous emission (SASE) FEL. A high-bunch-charge, low-emittance electron gun is followed by some initial acceleration to typically 100 MeV. In the following, magnetic chicanes help to compress the bunch and therefore increase the peak current. This happens at different energies to take care of beam dynamic effects that would deteriorate the bunch emittance in the case of too early compression at too low energies. Thus, the linac is separated by several such chicanes. The European XFEL main linac accelerates the beam in three sections, following the first acceleration in the injector.

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2.2 Injector

The injector design of the European XFEL is visibly affected by the need for long bunch trains, which are required for the efficient use of superconducting linac technology. Like many other FELs, it starts with a normal-conducting 1.6 cell radio frequency (RF) electron gun but here the source has to deliver 600 µs long trains, i.e., the RF on time is equivalently long, and not just some few microseconds. The 6 MeV electron beam produced is almost immediately injected into the first superconducting accelerator section, which allows efficient acceleration of bunch trains. This first linac section consists of a standard eight-cavity XFEL module, followed by a harmonic 3.9 GHz module. The latter is needed to manipulate the longitudinal beam profile, together with the later bunch compression in magnetic chicanes. Beam diagnostics are used to verify the electron beam quality at an energy of about 130 MeV. The injector installation, which is 50 m long in total, ends with a beam dump that is able to take the full beam power.

The injector of the European XFEL was commissioned and operated during the installation period of the main linac sections. The first beam was accelerated in December 2015. At the end of the injector, 600 µs long electron bunch trains of typically 500 pC bunches are available, with measured projected emittances of 1–1.5 mm mrad. Most relevant for the FEL process is the slice emittance, which was found to be of the order of 0.5 mm mrad for 500 pC.

The next section downstream of the injector is a warm beamline including a so-called dogleg and the first bunch compressor, for historical reasons named BC0. The dogleg takes care of the vertical offset between the injector tunnel and the main linac tunnel.

Compression in all bunch compressors is obtained by creating different path lengths in a four-dipole magnet chicane. Electrons with slightly lower beam energy are deflected more strongly and thus pass the chicane on an ‘outward curve’. The acceleration in the injector section is slightly off-crest, i.e., the energy of the leading electrons in the bunch is intentionally smaller. The aforementioned 3.9 GHz harmonic system helps to achieve the proper energy modulation along the bunch. Since all electrons have essentially the same speed, the leading ones travel for slightly longer, and the bunch is compressed.

At the XFEL bunch compressor BC0 there is a first slight compression, by roughly a factor of two. The bunches ready for further acceleration reach 1 mm length, ≈100 A peak current, with an energy spread of 1.5% at 130 MeV beam energy.

At present, the European XFEL uses the lower of two injector tunnels. The second one was originally built to install a copy of the first injector—availability depending on reliable injector operation was the issue. Meanwhile it seems to be more adequate to aim for a different injector, favouring longer pulse or even continuous wave operation.

2.3 First linac section, L1

The first section of the main linac consists of four superconducting XFEL accelerator modules operated at 1.3 GHz. Since each module houses eight ≈1 m long superconducting structures, and since the required energy increase is only 470 MeV—the bunch compression scheme asks for ≈600 MeV at BC1—the accelerating gradient in the first linac section is very moderate and well below the XFEL design gradient of 23.6 MV/m. In fact, the failure of a few cavities could easily be compensated. With respect to the RF operation, the first four modules represent a standard XFEL unit, since all four are connected to a single 10 MW multibeam klystron [5]. While the injector klystrons are located outside the accelerator tunnel, the configuration of this first RF power station is identical to all other downstream stations: the modulator is installed outside the tunnel, the pulse transformer and the klystron, with its waveguide distribution, are located below the accelerator modules (see also Fig. 1). Special care is taken to improve the availability of the first linac section. The low-level RF control, installed in shielded compartments next to the klystron, is duplicated, with the possibility of switching between the two systems without tunnel access.

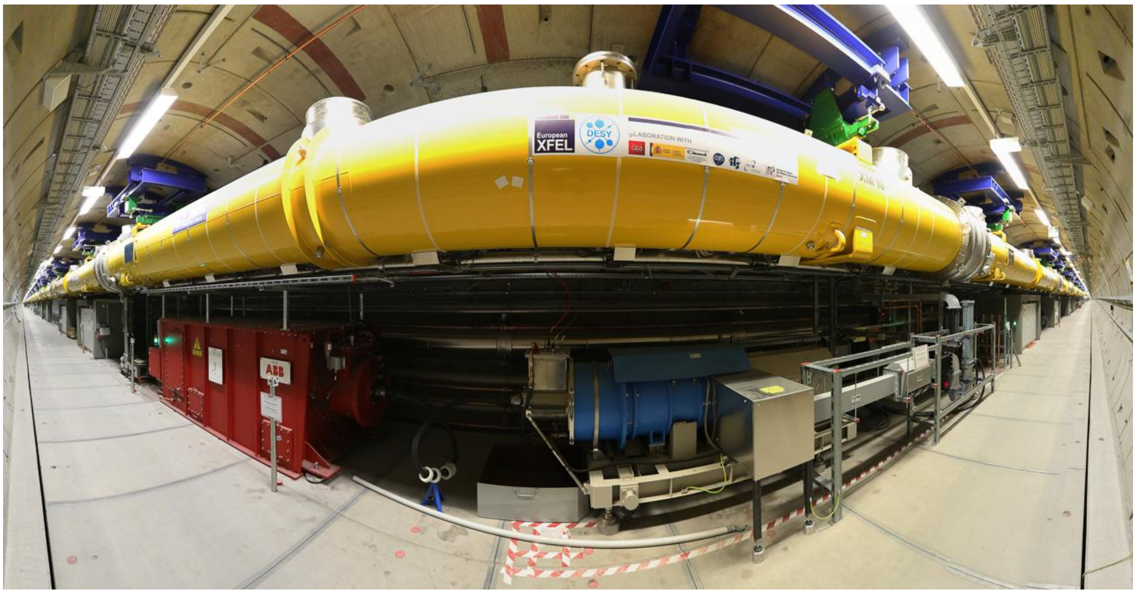

Fig. 1: Wide-angle photograph showing some few metres of the, in total, almost 1 km long superconducting linac of the European XFEL. The yellow accelerator module (length 12.2 m) is suspended from the ceiling. It houses eight superconducting structures. All installed 96 main linac modules are the result of a strong collaborative effort. Subcomponents were contributed by different partners, assembly [2, 3] was done at Saclay, France, and final cold testing [4] was carried out in the accelerator module test facility at DESY, Hamburg.

2.4 Bunch compression in BC1

The next section, starting at ≈100 m deep in the main linac tunnel (called XTL), is the bunch compression chicane, BC1.

The BC section needs four dipole magnets, further focusing elements, and beam diagnostics. Since this warm beamline section is close to the preceding, as well as to the succeeding, cold linac section, particle-free preparation of ultrahigh vacuum systems is essential. Here, the work had already started during the design phase of all respective beamline components. Cleaning methods had to be considered early on, and movable parts are to be avoided wherever possible. In consequence, the chicane vacuum chambers are wide and flat (in the vertical plane); changing the compression factor by shifting the beam to different paths does not involve moving the vacuum chambers mechanically. Here, the European XFEL design differs from normal-conducting linac designs, which are usually less restrictive with respect to particle cleanliness.

2.5 Second linac section, L2

The BC1 compressor is followed by a 12 accelerator module section (called L2). This altogether 150 m long superconducting linac is supposed to increase the electron beam energy to 2.4 GeV. The required average gradient is, at 18.75 MV/m, still moderate. Also here a conservative design gradient was chosen. Conversely, the installation of intentionally high-performance modules—accelerating gradients of around 30 MV/m were achieved in many module tests—can be and in fact has been done, again to increase the availability of a beam with sufficiently high energy, here at bunch compressor BC2. In addition, an energy increase at BC2 during parameter optimization becomes possible. From the point of view of the RF station, L2 consists of three identical RF stations with a pulse transformer and klystron every 50 m. Cryogenic-wise, L2 forms a standard unit. Altogether, 12 modules are connected to one cryogenic string, i.e., one long cryostat without intermediate separation valves. All linac sections have a cryogenic feed- and end-box, both connecting to the cryogenic bunch compressor bypass lines linking the different linac sections.

2.6 Final bunch compression in BC2

Downstream of L2, the last bunch compressor BC2 is installed, which basically repeats the functionality of BC1, here with the goal of producing the final electron bunch length required for lasing. A bunch length of 0.02 mm, corresponding to a 5 kA peak current, with a relative energy spread of 0.3% at 2.4 GeV beam energy will be produced. The section includes a transverse deflecting system as an essential beam diagnostic device. Single bunches are picked and deflected transversely to convert the short bunch length into a corresponding transverse beam size that can then be measured.

2.7 Main linac section, L3

Downstream of BC2, the linac L3 starts with a design length of more than 1 km. The actually installed length, including the cryogenic string connection and end boxes, is 984 m. Taking into account all installed main linac accelerator modules—4 in L1, 12 in L2, and 80 in L3—the achievable electron beam energy is greater than the European XFEL design energy of 17.5 GeV. The exact value will depend on the optimization of the low-level RF (LLRF) control, and here especially on the regulation reserve needed as a function of the electron beam current.

The main linac ends after 96 accelerating modules, corresponding to nine cryogenic strings, or 24 RF stations. The shortening by four accelerating modules was because of beamline vacuum leaks in two modules that could not be repaired in a timely manner. A third module suffers from a small leak in one of the cryogenic process lines. Thus, one RF station, equivalent to four modules, was omitted; this was legitimated by the excellent performance of many accelerator modules. A temporary transport beamline was installed, which is then followed by some further transport and a collimation beamline, protecting the downstream undulator beamlines from beam-halo and mis-steered beams in case of linac problems.

2.8 Beam transport, collimation, and distribution to the different undulators

Downstream of the linac, the electron beamline is also supported from the ceiling, over a length of 600 m. This keeps the tunnel floor free for transport and installation of electronics. Especially at the end of the 5.4 m diameter tunnel, where three beamlines (to SASEs 1 and 3, SASE 2, and into the linac dump) run in parallel, installation and maintenance of the components posed a considerable challenge. During accelerator operation, the electrons are distributed with a fast-rising flat-top strip-line kicker into one of the two electron beamlines. Another kicker system is capable of deflecting single bunches into a dump beamline. This allows for a free choice of the bunch pattern in each beamline, even with the linac operating with constant beam loading.

All undulators and photon beamlines are located in a fan-like tunnel. Figure 2 shows the arrangement of two hard X-ray undulators (SASE 1 und SASE 2), and a soft X-ray undulator (SASE 3), installed downstream of SASE 1. Each undulator provides X-ray photon beams for two different experiments. The time structure of the photon beams reflects the electron bunch pattern in the accelerated bunch trains, affected by the kicker systems.

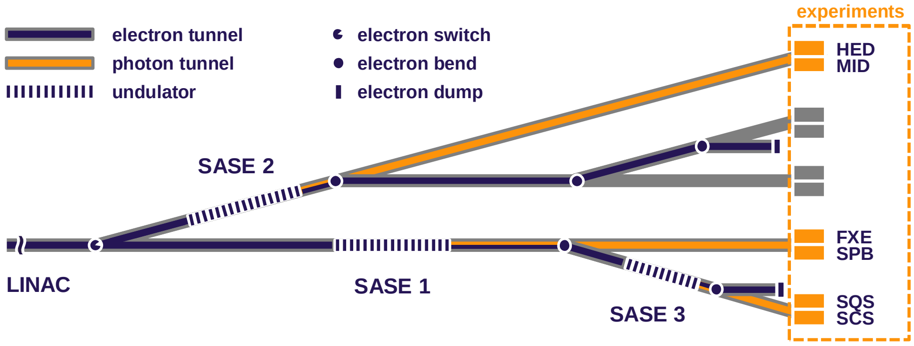

Fig. 2: Arrangement of two hard X-ray undulators (SASE 1 und SASE 2) and a soft X-ray undulator (SASE 3) installed downstream of SASE 1.

The fan-shaped tunnel system houses two electron beam dumps. Here the electrons are stopped after separation from the photon beams. Each dump can handle up to 300 kW beam power. An identical beam dump is located further upstream, at the end of the main linac tunnel (not shown in Fig. 2). Thus, accelerator commissioning and also beam operation is possible while installation or maintenance work in the undulator and photon beam tunnels is ongoing. All five photon beam tunnels end at the experimental hall. During initial operation, two experiments each are set up at three beamlines.

3 Overview of accelerator in-kind contributions

As described, the European XFEL project benefits from in-kind contributions provided by many partners. In the following, an overview is given, which allows understanding of the responsibilities within the project. The description essentially follows the project structure, i.e., contributions to the superconducting linac are listed first, followed by assignments related to the other sections of the accelerator complex. Infrastructure tasks are also described.

3.1 Cold linac contributions

Building the world’s largest superconducting linac was only possible in collaboration. Sufficiently developed superconducting RF expertise was required. Major key players already working together in the TESLA linear collider R&D phase joined the European XFEL in an early phase. During the XFEL construction phase, DESY had several roles. The accelerator complex, including the superconducting linac, required coordination. At the same time, large in-kind contributions in the field of superconducting RF technology were made. Work packages contributing to the cold linac are, in all cases, co-led by a DESY expert and a team leader from the respective contributing institute. Integration into the linac installation and infrastructure was another task. The commissioning and operation of the accelerator complex is delegated to DESY.

The accelerator of the European XFEL is assembled from superconducting accelerator modules contributed by DESY (Germany), CEA Saclay, LAL Orsay (France), INFN Milano (Italy), IPJ Swierk, Soltan Institute (Poland), CIEMAT (Spain), and BINP, Russia. The overall design of a standard XFEL module was developed in the frame of TESLA linear collider R&D. Final modifications were made for the required large-scale industrial production. Further details of the contributions to the superconducting accelerator modules can be found in Ref. [3].

3.2 Contributions to the cold linac infrastructure

Operation of the superconducting accelerator modules requires the extensive use of dedicated infrastructure. DESY provided the RF high-power system, which includes klystrons, pulse transformers, connection modules and matching networks, high-voltage pulse modulators, preamplifiers, power supplies, RF interlocks, RF cables, and waveguide systems. During the design and development phase, the 10 MW multibeam klystrons used were developed together with industrial partners. In total, 27 klystrons were finally ordered from two vendors. Pulse transformers were procured as one batch from one company. The modules connecting klystrons and pulse transformers were developed and built in collaboration with BINP Novosibirsk. Each klystron supplies RF power for 32 superconducting structures, i.e., four accelerator modules. The waveguide system used takes care of sophisticated RF power matching [6]. The individual accelerating gradients, determined by module tests, are considered for a special tailoring of the distribution system. To optimize the RF control, both outputs of the multibeam klystron deliver roughly the same power, which is realized by a sorting of the accelerator modules before tunnel installation.

The LLRF system that controls the accelerating RF fields of the superconducting modules is another major DESY contribution. Precision regulation of the RF fields inside the accelerating cavities is essential to provide a highly reproducible and stable electron beam. The RF field regulation is achieved by measuring the stored electromagnetic field inside the cavities. This information is further processed by the feedback controller to modulate the driving RF source. Detection and real-time processing are performed using the most recent field programmable gate array (FPGA) techniques. Performance increase demands a powerful and fast digital system, which was realized with the Micro Telecommunications Computing Architecture (MicroTCA.4). Fast data transfer and processing is achieved by FPGAs within one crate, controlled by a CPU. In addition to the MicroTCA.4 system, the LLRF comprises external supporting modules, also requiring control and monitoring software. During the XFEL construction phase, DESY was operating the Free Electron Laser (FLASH), which is a user facility of the same type as the European XFEL but at a significantly lower maximum electron energy of 1.2 GeV. The LLRF system for FLASH is equal to that of the European XFEL, which allowed for testing, developing, and performance benchmarking in advance of the European XFEL commissioning [7].

BINP Novosibirsk produced and delivered major cryogenic equipment for the linac, such as valve boxes and transfer lines. The cryogenic plant itself was an in-kind contribution of DESY.

3.3 Contributions to the warm linac sections

The largest visible contributions to the warm beamline sections are the >700 beam transport magnets and the 3 km vacuum system in the different sections. While most of the magnets were delivered by the Efremov Institute, St. Petersburg, a smaller fraction were built by BINP Novosibirsk. Many metres of beamline, either simple straight chambers or quite sophisticated flat bunch compressor chambers, were also fabricated by BINP Novosibirsk. DESY made a careful incoming inspection, including particle cleaning when necessary.

State-of-the art electron beam diagnostics are of essential importance for the success of an FEL. Thus, 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. Longitudinal bunch properties are measured by bunch compression monitors, beam arrival monitors, electro-optical devices, and, most notably, transverse deflecting systems. Production of the sensors and readout electronics is basically finished. Prototypes of all devices have been tested at FLASH. BPM electronics were developed by the Paul-Scherrer-Institut, Villigen, and showed, together with the DESY built pick-ups, performance exceeding the specifications [8, 9].

4 Accelerator status at the start of commissioning

As of autumn 2016, the installation work in the main accelerator tunnel will be finished. All linac sections except for the last cryogenic strings (eight accelerator modules) will be ready for cold commissioning. The complete linac will be cooled to operating temperature. The last cryogenic string requires final actions, such as finishing the waveguide systems, commissioning of the technical interlock system, or, for a few components, even finishing installation of signal cables. The respective work will be done during maintenance access.

4.1 Cold linac status

Installation of, in total, 96 main linac accelerator modules was finished in September 2016. The original plan to get one module per week ready for tunnel installation was basically fulfilled. Modules assembled at CEA Saclay came to DESY and were tested. Test results were used to define the RF power distribution, which was then realized by a proper tailoring of the waveguide system. Sorting of modules helped to find an optimum in the grouping of four modules connected to each multibeam klystron. Finally, some prognosis with respect to the achievable linac energy can be made. Neglecting the working points of the bunch compressors, and looking only at the accelerator modules' usable gradients, as determined during the cold test after arrival at DESY, the sum of all individual accelerator modules' usable gradients is about 22 GeV. Respecting the constraints of the possible RF power distribution leads to a reduction to 21 GeV, corresponding to an average gradient of 27.5 MV/m. The European XFEL linac by far exceeds the design gradient of 23.6 MV/m. Details are given in Ref. [4].

It is expected that during cold commissioning some accelerator cavities or the respective associated systems (RF power coupler, waveguide, LLRF) will show some unforeseen limitations. The European XFEL design included one RF station (i.e., four modules) as spare. Thus, it is correct to state conservatively that the designed 17.5 GeV final energy can be safely reached. The excess in energy will give a higher availability.

The nominal working point of BC2 is 2.4 GeV, while the current highest possible working point is 3.3 GeV, which would bring the final energy to about 19.5 GeV, assuming that all systems are in operation and close to their limit.

Completing the picture of the accelerator module performance, the following can be stated.

- To make 808 superconducting cavities available for 101 accelerator modules, fewer than 1% extras were required. This is based on indispensable quality measures in the full production chain [10].
- Although many accelerator modules needed correction of non-conformities (component or assembly related), discovered either during assembly or even later during test at DESY, in the end, only three modules were not ready for installation in time. Nevertheless, sufficient expertise was required at all partner laboratories.
- Most challenging for the cold linac team was the availability of the RF power couplers. Quality issues, often, but not exclusively, related to the copper plating of stainless steel parts, and the resulting schedule challenges, were faced. The experienced supply chain risk required a large degree of flexibility and willingness to find corrective measures.

4.2 Other sections of the accelerator complex

The installation of all beamline sections from the injector to the end of the main linac tunnel (XTL) will be finished at the time of linac cool-down. Beam transport to the linac commissioning dump after 2.1 km will be possible.

After the linac, almost 3 km of electron beamlines distribute the beam through the SASE undulators to the three different beam dumps. In the northern branch, housing the SASE1 and SASE3 undulators, most of the beamline sections are ready. All undulators are in place. During the last quarter of 2016, the northern branch of tunnels will be completed. The southern branch, housing SASE 2, is scheduled for the first quarter of 2017.

5 Conclusion

The installation of the European XFEL accelerator complex comes to an end. While the linac sections are finished and cool-down and commissioning follows, the remaining beamline sections will be finalized in the next months. First lasing in the SASE 1 undulator is expected for spring 2017, about 6 months after the start of the linac cool-down

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The European XFEL was built in a huge collaborative effort, accompanied by an immense team spirit of the involved partners. The author would like to thank all colleagues working as work package leaders, supervisors, key experts, field workers, or backstage helpers. Useful information of the project structure and an overview about in-kind contributions are available [11, 12].

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