

# THE EUROPEAN XFEL – STATUS AND COMMISSIONING\*

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## Abstract

The European XFEL under construction in Hamburg, Northern Germany, 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 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 is next. First lasing is expected for spring 2017. The paper summarizes the status of the project. First results of the injector commissioning are given.

## 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 coordinates the European XFEL Accelerator Consortium but also contributes with many accelerator components, and the technical equipment of buildings, with its associated general infrastructure. With the finishing of the accelerator installation, the commissioning phase is now starting, with cool down of the main linac scheduled for end of November 2016.

## LAYOUT OF THE EUROPEAN XFEL

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

### *Introduction to the Accelerator*

The European XFEL with its total facility length of 3.4 km follows the established layout of high performance single pass Self-Amplified Spontaneous Emission (SASE) FELs. A high bunch charge, low emittance electron gun is followed by some first 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 which would deteriorate the bunch emittance in case of too early compression at too low energies. Thus the linac is separated by several of such chicanes. The European XFEL main linac accelerates the beam in three sections, following the first acceleration in the injector.

### *Injector*

The injector design of the European XFEL is visibly affected by the need of 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  $\mu$ s long trains i.e. the rf-on time is equivalently long, and not just some few  $\mu$ s. The produced 6 MeV electron beam 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 is used to verify the electron beam quality at energy of about 130 MeV. The in total 50 m long injector installation ends with a beam dump being 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. First beam was accelerated in 12/2015. At the end of the injector, 600  $\mu$ s long electron bunch trains of typ. 500 pC bunches are available with measured projected emittances of 1 to 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 beam line 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 reached by creating different path lengths in a four dipole magnet chicane. Electrons with slightly lower beam energy are deflected stronger and thus pass the chicane on an ‘outward curve’. The acceleration in the injector section is done slightly off-crest, i.e. the energy of the leading electrons in the bunch is intentionally lower. The above mentioned 3.9 GHz harmonic system helps to get the proper energy modulation along the bunch. Since all electrons have essentially the same speed, the leading ones travel slightly longer, and the bunch is compressed.

The XFEL bunch compressor BC0 does a first slight compression by roughly a factor 2. The bunches ready for further acceleration reach 1 mm length, approx. 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 favoring longer pulse or even continuous wave (CW) operation.

\* Work supported by the respective funding agencies of the contributing institutes; for details please see <http://www.xfel.eu>

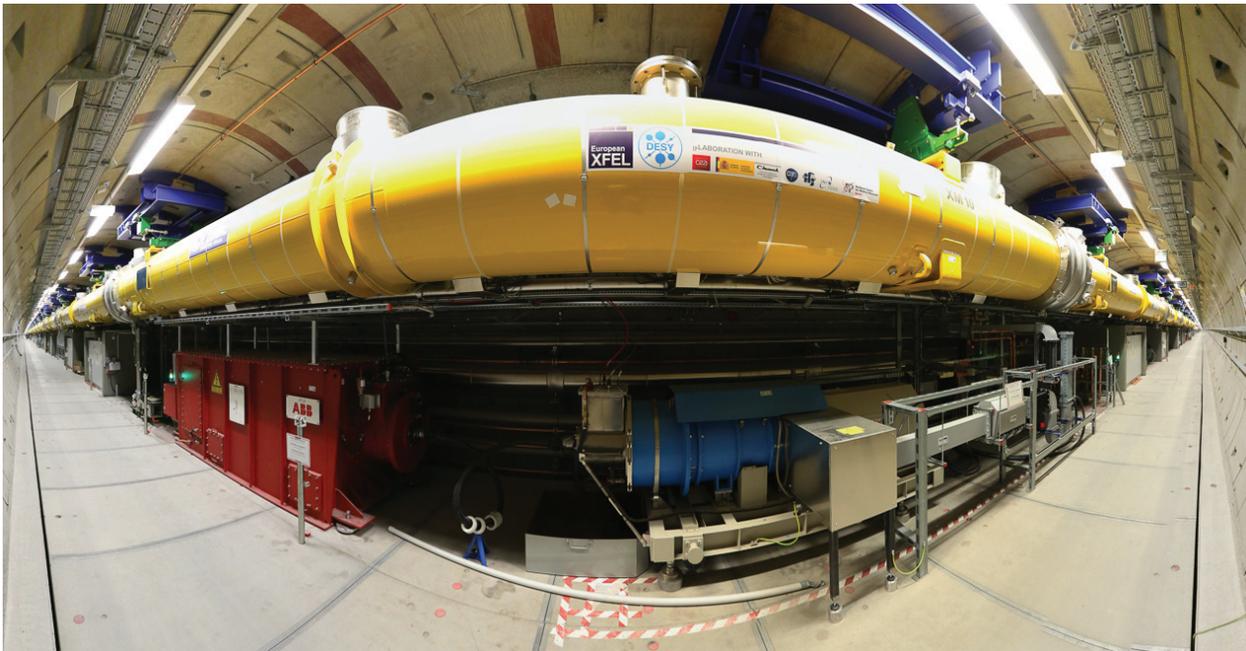


Figure 1: Wide angle photography showing some few meters of the in total almost 1 kilometer long superconducting linac of the European XFEL. The yellow accelerator module (length 12.2 m) is suspended from the ceiling. It houses eight superconducting structures. All installed 96 main linac modules are 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.

### *The First Linac Section L1*

The first section of the main linac consists of four superconducting (s.c.) XFEL accelerator modules operated at 1.3 GHz. Since each module houses eight approx. 1 m long s.c. structures, and since the required energy increase is 470 MeV only – the bunch compression scheme asks for approx. 600 MeV at BC1 –, the accelerating gradient in the first linac section is very moderate and very well below the XFEL design gradient of 23.6 MV/m. In fact, the failure of some few cavities could be easily compensated. With respect to the rf operation, the first four modules are representing a standard XFEL unit since all four are connected to one single 10 MW multi-beam 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 is 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 to switch between the two systems without tunnel access.

### *Bunch Compression in BC1*

The next section, starting at approx. 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

beam line section is close to the preceding as well as to the succeeding cold linac section, particle free preparation of ultra-high vacuum systems is essential. Here the work started already 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 require mechanically moving the vacuum chambers. Here the European XFEL design differs from normal conducting linac designs which are usually less restrictive with respect to particle cleanliness.

### *The Second Linac Section L2*

The BC1 compressor is followed by a twelve 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 with 18.75 MV/m still moderate. Also here a conservative design gradient was chosen. On the other hand, the installation of intentionally high performance modules – accelerating gradients around 30 MV/m were reached in many module tests – can be and in fact was done to again increase the availability of a beam with sufficiently high energy, here at bunch compressor BC2. Also an energy increase at BC2 during parameter optimization becomes possible. From the rf station point of view the linac section L2 consists of three identical rf stations with pulse transformer and klystron every 50 m. Cryogenic-wise L2 forms a stand-

ard 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.

### 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 to produce the final electron bunch length required for lasing. A bunch length of 0.02 mm corresponding with 5 kA peak current, with a relative energy spread of 0.3% at 2.4 GeV beam energy will be reached. The section includes a transverse deflecting system as an essential beam diagnostic device. Single bunches are picked and deflected transversely which converts the short bunch length into a corresponding transverse beam size which then can be measured.

### The 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 – four in L1, twelve in L2, and 80 in L3 – the achievable electron beam energy is above the European XFEL design energy of 17.5 GeV. The exact number will depend on the optimization of the 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, which corresponds to 9 cryogenic strings, or 24 RF stations. The shortening by four accelerating modules was due to beam line vacuum leaks in two modules which 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 left out which was legitimated by the excellent performance of many accelerator modules. A temporary transport beam line was installed which then is followed by some further transport and a collimation beam line protecting the downstream undulator beam lines from beam-halo and mis-steered beams in case of linac problems.

### Beam Transport, Collimation and Distribution to the Different Undulators

Downstream of the linac the electron beam line is also 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 SASE 1 & 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 beam lines. Another kicker system is capable of deflecting single bunches in a dump beam line. This allows for a free choice of the bunch pattern in each beam

line 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.

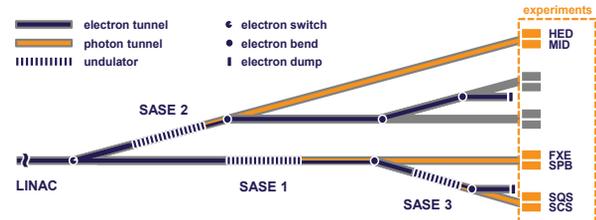


Figure 2: arrangement of two hard x-ray undulators (SASE 1 und SASE 2), and a soft x-ray undulator (SASE 3) installed downstream of SASE 1.

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.

## OVERVIEW ABOUT ACCELERATOR IN-KIND CONTRIBUTIONS

As described above the European XFEL project benefits from in-kind contributions provided by many partners. In the following an overview is given which allows understanding 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 described also.

### Cold Linac Contributions

Building the worldwide largest superconducting linac was only possible in collaboration. Sufficiently developed SRF expertise was required. Major key-player 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 SRF technology were contributed. 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 out of superconducting accelerator modules being 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 done for the required large scale industrial production. Further details about the contributions to the superconducting accelerator modules can be found in [3].

### *Contributions to the Cold Linac Infrastructure*

The 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 & development phase, the used 10 MW multi-beam klystrons were developed together with industrial partners. In total 27 klystrons were finally ordered at two vendors. Pulse transformers were procured as one batch from one company. The modules connecting klystron and pulse transformer were developed and built in collaboration with BINP Novosibirsk. Each klystron supplies RF power for 32 superconducting structures, i.e. four accelerator modules. The used waveguide system takes care of a sophisticated rf power matching [6]. The from module tests known individual accelerating gradients are considered for a special tailoring of the distribution system. In order to optimize the rf control, both outputs of the multi-beam klystron deliver roughly the same power which is realized by a sorting of the accelerator modules before tunnel installation.

The Low Level RF System (LLRF) controlling 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. RF field regulation is done 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 most recent field programmable gate array (FPGA) techniques. Performance increase demands a powerful and fast digital system, which was found with the Micro Telecommunications Computing Architecture (MicroTCA.4). Fast data transfer and processing is done 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 the one of 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.

### *Contributions to the Warm Linac Sections*

The largest visible contributions to the warm beam line sections are the over 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 was built by BINP Novosibirsk. Many meters of beamline, be it simple straight chambers or the quite sophisticated flat bunch compressor chambers, were also fabricated by BINP Novosibirsk. DESY took care of a careful incoming inspection, whenever necessary including particle cleaning.

State of the art electron beam diagnostics is 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 notable transverse deflecting systems. Production of the sensors and read-out electronics is basically finished. Prototypes of all devices have been tested at FLASH. BPM electronics was developed by the Paul-Scherrer-Institut, Villigen and showed, together with the DESY built pickups, performance exceeding the specifications [8, 9].

## **ACCELERATOR STATUS AT THE START OF COMMISSIONING**

As of fall 2016 the installation work in the main accelerator tunnel will be finished. All linac sections but the last cryogenic strings (8 accelerator modules) will be ready for cold commissioning. The complete linac will be cooled down to operating temperature. The last cryogenic string (CS) requires final actions like finishing the waveguide systems, commissioning of the technical interlock system or for some few components even finishing of signal cables installation. The respective work will be done during maintenance access.

### *Cold Linac Status*

Installation of in total 96 main linac accelerator modules was finished in 9/2016. 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 (see above). Sorting of modules helped to find an optimum in the grouping of for modules each connected to one multi-beam klystron. Finally some prognosis with respect to the achievable linac energy can be made. Neglecting the working points of the

bunch compressors, and only looking 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 with 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 [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 conservatively state 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 at present highest possible working point is 3.3 GeV, which would bring the final energy to about 19.5 GeV, assuming all systems in operation and close to their limit.

Completing the picture of the accelerator module performance it can be stated:

- In order to make 808 superconducting cavities available for 101 accelerator modules less than 1% extras were required. This 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, at 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 lot of flexibility and willingness to find corrective measures.

### *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 beam lines 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 Q1/2017.

## CONCLUSION

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

## ACKNOWLEDGEMENT

The European XFEL was built in a great collaborative effort accompanied by an immense team spirit of the involved partners. The author would like to thank all colleagues working as work package leader, as supervisor, as key expert, as field worker, or as backstage helper. Useful information about the project structure and an overview about in-kind contributions are available [11].

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