ACCELERATOR TECHNICAL PROGRESS AND FIRST COMMISSIONING RESULTS FROM THE EUROPEAN XFEL*

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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 2 keV out of three undulators that can be operated simultaneously with up to 27,000 bunches per second. The FEL is driven by a 17.5 GeV super-conducting linac. Installation of this linac is now finished and commissioning is next. First lasing is expected for spring 2017. This 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 in-kind [2]. 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. The main milestones of the European XFEL project with focus on the accelerator are as follows:

- 07/2006: XFEL TDR [1]published
- 01/2009: start of underground construction
- 08/2014: start installation of accelerator components
- 12/2015: start of injector commissioning
- 10/2016: cool-down of XFEL linac, start of commissioning
- 07/2017: start user operation.

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 as depicted in Figure 1.

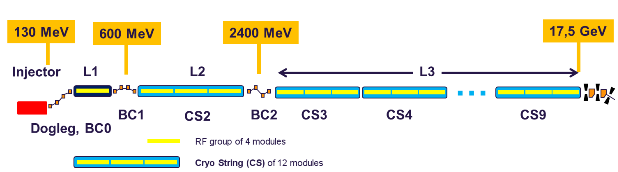

Figure 1: Schematic layout of the major sections of the XFEL accelerator.

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 L1, L2, and L3, following the first acceleration in the injector.

The XFEL linac was designed with an electron beam energy of 17.5 GeV provided by 100 super-conducting (s.c.) modules (plus 1 in the injector) of 12.2 m length suspended from the tunnel ceiling, operated at 1.3 GHz. Each modules houses 8 s.c. cavities of about 1 m length. 4 such modules are forming 1 standard RF unit consisting of a modulator (outside the tunnel), a pulse transformer and 10 MW multi-beam klystron [3] (both located in the tunnel underneath the accelerator modules, see Fig. 2). 3 RF units (consisting of a total of 12 accelerating modules) form 1 standard cryogenic unit called a cryo-string (CS2 to CS9 in Fig. 1). With a design gradient of 23.6 MV/m 1 RF unit with 4 accelerator modules was intended as spare.

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 s.c. linac technology. Like many other FELs it starts with a normal-conducting 1.6 cell radio frequency (RF) electron gun delivering 600 μs long trains followed almost immediately by a first s.c. accelerator section which allows efficient acceleration of bunch trains. This first linac section consists of a standard XFEL module, followed by a harmonic 3.9 GHz module. Unlike the standard RF units described above, the 2 klystrons for the injector module are located outside the injector tunnel. The 3rd harmonic system 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. A transverse deflecting system is installed which consists of a 550 mm long 3 GHz RF structure, able to streak individual bunches out of the bunch train vertically. These bunches will be kicked to the off axis screens to examine the longitudinal profile and slice emittance. The in total 50 m long injector installation ends

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with a beam dump being able to take the full beam power allowing to commission and operate in injector independently of activities downstream in the main linac tunnel.

The next section downstream of the injector is a warm beam line including a so-called dogleg and the first bunch compressor (Fig. 1), for historical reasons named BC0. The dogleg takes care of the vertical offset between the injector tunnel and the main linac tunnel.

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 after being accelerated by the standard XFEL module in the injector.

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.

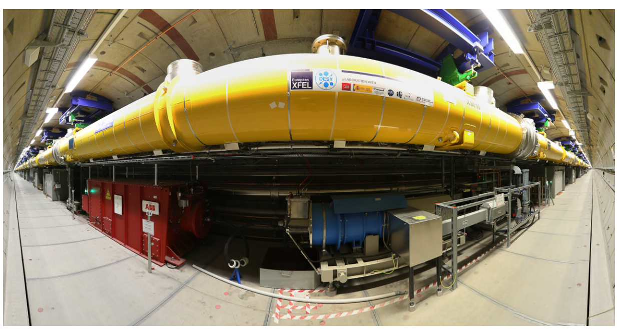

Figure 2: Wide angle photography showing some few meters of the in total almost 1 km long s.c. linac of the European XFEL. Below a unit of 4 modules (yellow) a pulse transformer (red) and a klystron (blue) of the RF station is installed among other infrastructure.

The First Linac Section L1

The first section of the main linac L1 consists of four s.c. XFEL accelerator. Since the required energy increase required by the following BC section is 470 MeV only, the accelerating gradient in L1 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. The first four modules are representing a standard XFEL RF unit. 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.

All linac sections have a cryogenic feed- and end-box, both connecting to the cryogenic bunch compressor bypass lines linking the different linac sections.

Bunch Compression in BC1

The next section (Fig. 1), 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. A bunch length of 0.1 mm corresponding to 1 kA peak current, with a relative energy spread of 1% at 600 MeV beam energy will be reached at the end of BC1.

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 beam-line 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, Fig. 1). This altogether 150 m long s.c. linac section 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.

Final Bunch Compression in BC2

Downstream of L2 (see Fig. 1) 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 to 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 (see again Fig. 1). 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 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. This section is then followed by some 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 XTL tunnel, where 3 beam-lines (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 beam lines are located in a fan-like tunnel. Figure 3 shows the arrangement of two hard x-ray undulators (SASE 1 and 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.

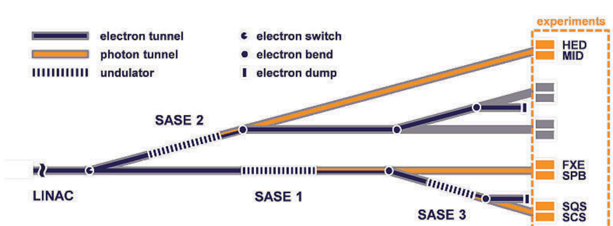

Figure 3: Arrangement of two hard x-ray undulators (SASE 1 and SASE 2), and a soft x-ray undulator(SASE 3) installed downstream of SASE 1.

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. 3). 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 beam-lines.

IN-KIND CONTRIBUTIONS TO THE ACCELERATOR

As mentioned above the European XFEL project benefits from in-kind contributions provided by many partners.

Building the worldwide largest super-conducting linac was only possible in collaboration. Sufficiently developed SRF 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 s.c. 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 s.c. 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 super-conducting accelerator modules can be found in [5]. A more detailed description of the various in-kind contributions to the accelerator complex was also reported in [2].

INJECTOR COMMISSIONING

The overall project schedule of the XFEL always included an early completion of the injector before work would be finished in the main linac tunnel. The scheduled advancement of the injector by about 1 year was to be utilized to commission the injector and all its sub-components to allow routine operation at the specified parameter sets. With the injector containing most of the same components installed in the main linac as well, the early commissioning would give extremely valuable experience for the later beam commissioning of the entire facility.

First beam operation with the RF gun of the injector alone already took place early 2015. The injector tunnel was closed finally in November 2015 and first electrons were accelerated to 130 MeV and buried in the dedicated injector beam dump on December 18, 2015. Until July 2016 the injector was operated 24/7 from the main control room at DESY and all commissioning goals of the injector were reached as summarized in Table 1.

A more detailed description of the XFEL injector and of the commissioning work is given in [6].

Table 1: Parameter Set Reached by the Injector Commissioning Meeting All Goals Set by the Commissioning Program. The slice emittance was specified for a gun cavity gradient of 60 MV/m at various bunch charges. The gun was operated for safety reasons at 52 MV/m. Slice emittance was studied with the TDS at about 0.5 nC bunch charge.

Quantity	achieved Value
macro pulse rep. rate	10 Hz
RF pulse length (flat top)	650 µs
bunch rep. frequency within pulse	4.5 MHz
bunch charge	0.1 - 1 nC
slice emittance	0.5 mm mrad

Emittance Measurements

A big part of the injector commissioning was focused on emittance studies and optimization. For this purpose 4 screen stations have been installed to measure the transverse emittance. Towards the end of the commissioning period, also the TDS became available to access the bunch profile and slice emittances. Emittance measurements were routinely performed using on-axis screens on trains of a few bunches, off-axis screens with fast kickers for individual bunches in a bunch train and doing quadrupole scans by varying the strength of individual quadrupoles and measuring the beam size on an on-axis screen. These measurements are in good agreement to about 10-15 % in terms of emittance.

The TDS allows a precise determination of the slice emittance along the bunch train. Due to the late availability of the system, measurements were performed mostly for bunch charges of 0.5 nC. Figure 4 shows such a measurement with a minimum value of about 0.5 mm mrad in the core of the bunch.

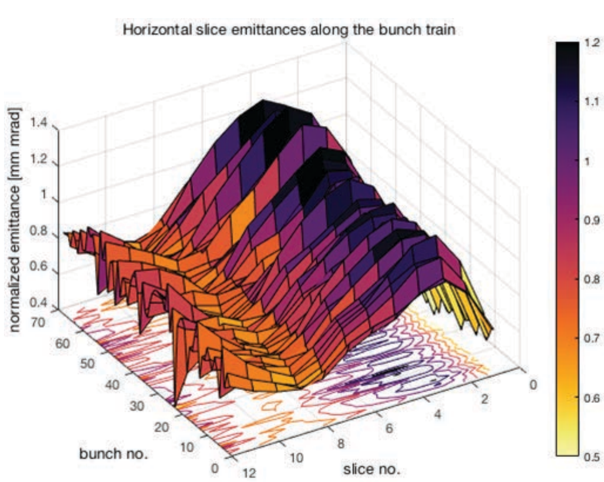

Figure 4: Slice emittance measurement with the TDS along a bunch train.

ACCELERATOR STATUS AT THE START OF LINAC COMMISSIONING

As of fall 2016 the installation work in the main accelerator- tunnel will be finished. All linac sections but the last two cryogenic strings CS8 (12 accelerator modules) and CS9 (8 modules) will be ready for cold commissioning. The complete linac will be cooled down to operating temperature. The last two CSs require final actions like commissioning of the technical interlock system or for CS9 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 [4] 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 [8]. Sorting of modules helped to find an optimum in the grouping of 4 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 (see Fig. 5). 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 [7].

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 unit 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 super-conducting cavities available for 101 accelerator modules less than 1% extras were required. This based on indispensable quality measures in the full production chain [9].
- 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.

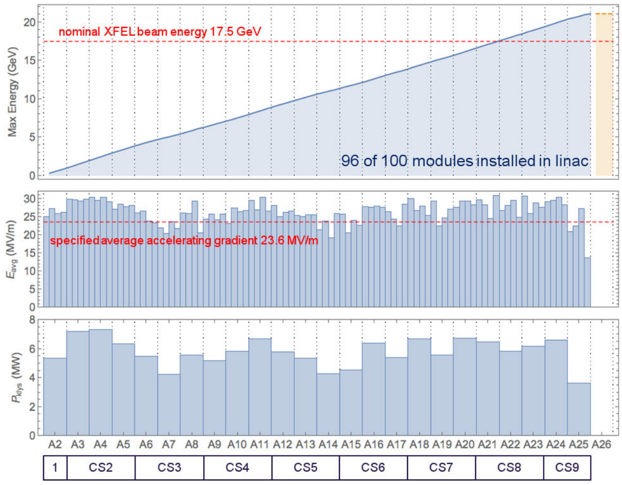

Figure 5: Module performance and energy reach of the s.c. XFEL linac [7].

- 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 beam-line 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 beam-line 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 cool-down / 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 [10].

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