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COMMISSIONING AND FIRST LASING OF THE EUROPEAN XFEL*

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on behalf of the European XFEL Accelerator Consortium and the Commissioning Team

Abstract

The European X-ray Free-Electron Laser (XFEL) in Hamburg, Northern Germany, aims at producing X-rays in the range from 0.25 up to 25 keV out of three undulators that can be operated simultaneously with up to 27,000 pulses per second. The XFEL is driven by a 17.5-GeV superconducting linac. This linac is the worldwide largest installation based on superconducting radiofrequency acceleration. The design is using the so-called TESLA technology which was developed for the superconducting version of an international electron positron linear collider. After eight years of construction the facility is now brought into operation. First lasing was demonstrated in May 2017. Experience with the superconducting accelerator as well as beam commissioning results will be presented. The path to the first user experiments will be laid down.

INTRODUCTION

The European XFEL aims at delivering X-rays from 0.25 to up to 25 keV out of three SASE undulators [1, 2]. The radiators are driven by a superconducting linear accelerator based on TESLA technology [3]. The linac operates in 10 Hz pulsed mode and can deliver up to 2,700 bunches per pulse. Electron beams will be distributed to three different beamlines, this within a pulse. Three experiments can be operated in parallel.

The European XFEL is being realized as a joint effort by 11 European countries (Denmark, France, Germany, Hungary, Italy, Poland, Russia, Slovakia, Spain, Sweden, and Switzerland). The accelerator of the European XFEL and major parts of the infrastructure are contributed by the accelerator construction consortium, coordinated by DESY. The consortium consists of CEA/IRFU (Saclay, France), CNRS/IN2P3 (Orsay, France), DESY (Hamburg, Germany), INFN-LASA (Milano, Italy), NCBJ (Świerk, Poland), WUT (Wrocław, Poland), IFJ-PAN (Kraków, Poland), IHEP (Protvino, Russia), NIIEFA (St. Petersburg, Russia), BINP (Novosibirsk, Russia), INR (Moscow, Russia), CIEMAT (Madrid, Spain), UPM (Madrid, Spain), SU (Stockholm, Sweden), UU (Uppsala, Sweden), and PSI (Villigen, Switzerland). DESY will also be responsible for the operation, maintenance and upgrade of the accelerator.

Construction of the European XFEL started in early 2009. The commissioning of the linear accelerator began end of 2015 with the injector, and end of 2016 with the cool-down of the main accelerator.

FACILITY LAYOUT

The complete facility is constructed underground, in a 5.2 m diameter tunnel about 25 to 6 m below the surface level and fully immersed in the ground water. The 50 m long injector is installed at the lowest level of a 7 stories underground building whose downstream end also serves as the entry shaft to the main linac tunnel. Next access to the tunnel is only about 2 km downstream, at the bifurcation point into the beam distribution lines. The beam distribution provides space for in total 5 undulators – 3 being initially installed. Each undulator is feeding a separate beamline so that a fan of 5 almost parallel tunnels, separated each by about 17 m, enters the experimental hall located 3.3 km away from the electron source.

The accelerator of the European XFEL starts with a photo-injector based on a normal-conducting 1.3 GHz 1.6 cell accelerating cavity [4]. A Cs2Te-cathode, illuminated by a Nd:YLF laser operating at 1047 nm and converted to UV wavelength, produces 600 µs long bunch trains of 2,700 bunches. The photo-injector is followed by a standard XFEL superconducting (s.c.) 1.3 GHz accelerating module, and a 3rd harmonic (3.9 GHz) linearizer, also housing eight 9-cell s.c. cavities. A laser-heater, a diagnostic section and a high-power dump complete the injector.

Figure 1: First bunch compression chicane.

The European XFEL uses a three stage bunch compression scheme. All magnetic chicanes are tuneable 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 (see Fig. 1). Special care was taken in the design of the vacuum chambers. There are no moving parts in order to min-

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imize the risk of particle creation and transportation in the vicinity of the superconducting linac. Diagnostic stations are placed after the second and third compression stage.

The superconducting linear accelerator consists of 96 TESLA type accelerator modules [5]. Always 4 modules are fed by one 10 MW multi-beam klystron providing sufficient RF power for high gradients, including regulation reserve. The accelerator modules are suspended from the ceiling (see Fig. 2), while the complete RF infrastructure (klystron, pulse transformer, LLRF electronics) is installed below the modules. The modulators are placed in one single hall above ground, and the high-voltage pulse is fed to the pulse transformer by up to 2 km long cables. After the linac a collimation section protects down-stream hardware in case of component failure, and collimates halo particles [6].

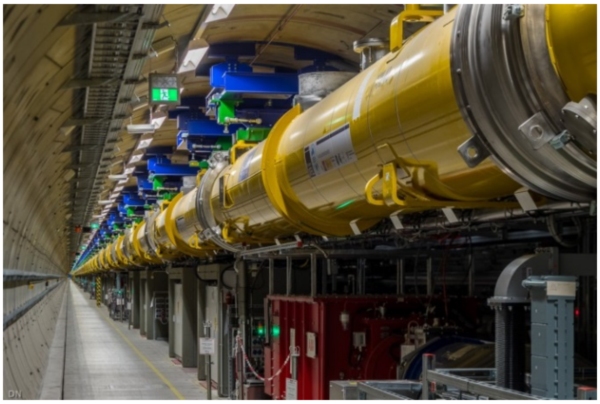

Figure 2: View into the linac tunnel with the accelerator modules suspended from the ceiling and the RF infrastructure placed below, on the floor.

Almost 2 km of electron beam line distribute the beam to the SASE undulators SASE1 and SASE3 (‘North Branch’) or SASE2 (‘South Branch’). The electrons are distributed with a fast rising flat-top strip-line kicker in one of the two electron beam lines. Another kicker system is capable of deflecting single bunches into a dump beam line. The distribution system allows for a free choice of the bunch pattern in each beam line even with the linac operating with long bunch trains and thus constant beam loading. Figure 3 summarizes the accelerator layout.

Electron bunch charges can be varied from 20 pC to 1000 pC [7], with resulting bunch length after compression ranging from 3 fs to 150 fs FWHM [8]. With three different linac energies (8.5, 14, and 17.5), and the variable gap undulators, photon energies from 0.25 keV to 25 keV can be covered.

COMMISSIONING RESULTS

Injector Commissioning

The injector is operated in a separate radiation enclosure, well separated from remaining tunnel installations. The beam dump at the end of the injector allows injector operation up to full beam power.

The superconducting accelerator of the injector was cooled down in December 2015 and first electrons were accelerated to 130 MeV on Dec. 18th [9]. Also at that early stage the 3rd harmonic lineariser was commissioned and from then on operated at the design gradient throughout the complete run [10]. The injector commissioning ended in July 2016, to connect the cryogenic distribution boxes of the main accelerator to the cryo-infrastructure.

Within this commissioning most of the design parameters of the European XFEL injector could be reached or even exceeded. Long bunch trains were produced and the measured slice emittance at 500 pC was between 0.4 and 0.6 mm mrad, depending on the measurement technique. Extensive emittance studies were made possible by a 4-off-axis-screen measurement stage. This enabled fast parameter scans and the study of the emittance evolution along long bunch trains [11]. Combined with a transverse deflecting structure, slice properties along the bunch train were measured.

For ultimate performance, the XFEL photo injector requires stable operation at RF power levels of about 6 MW. At these power levels the waveguide window and the cathode plug rf-contact showed reliability issues after some operating time. While solutions for these problems exist, their qualification needs long uninterrupted operation at high power levels [12]. Initially the XFEL is thus operated with a slightly reduced injector cavity gradient.

Cryogenic System

The European XFEL cryogenic system consists of two overhauled strings of the DESY HERA cryo-plant, a new distribution box and transfer line to the XFEL accelerator entrance shaft, cold compressors to reach 2K and further distribution boxes to distribute the He towards the injector. Finally, the long uninterrupted cryo-string of the linear accelerator together with its transfer and bypass-lines is also part of the cryogenic system. The cooling power was measured during the pre-commissioning. More than 1.9 kW in the 2 K circuit, 2.8 kW in the 5-8 K circuit, and 18 kW in the 40 – 80 K circuit were offered, all exceeding specifications. First cool down of the linac from room-temperature to 4 K was achieved during December 2016, with no cold leaks occurring. Start-up of the cold compressors enabled the handover of the accelerator at 2 K beginning of January. Regulation loops were optimized in the following weeks, and the pressure of the 2 K circuit can now be kept constant well below the requirement of ± 1% [13].

Electronics and Control System

The front end electronics for LLRF, high-power RF, beam diagnostics, vacuum and cryo-control is installed in shielded and temperature controlled compartments in the tunnel. The newly developed MTCA.4 standard is used throughout the installation [14, 15]. About 250 crates in the tunnel benefit from enhanced remote monitoring and maintenance capabilities, thus reducing the need for time-consuming on the spot interventions to a minimum.

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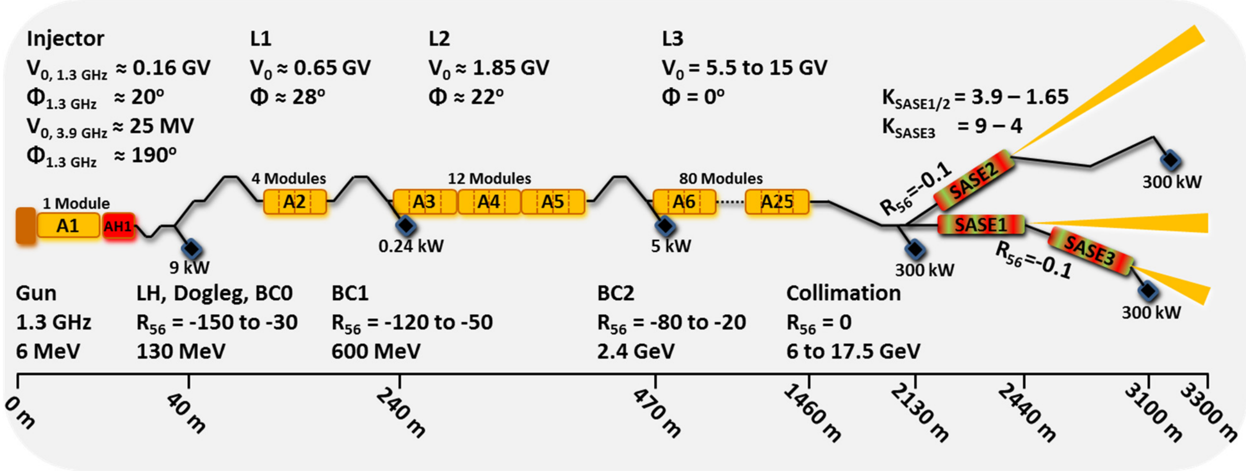

Figure 3: Schematic overview of the European XFEL accelerator. Single RF stations are named A*nn* and feed either one module (A1) or 4 modules (A2-A25). R_{56} ranges for the bunch compressors are given in mm, and the phases of the different linac sections refer to typical compression set-ups. The maximum allowed beam power of the three commissioning dumps after the injector and the 2nd and 3rd bunch compressor (BC1 and BC2) as well as of the main dumps after the linac and each beam distribution line is given.

The accelerator's main control system is DOOCS, while some part of the infrastructure is controlled using EPICS. Photon systems and experiments use the newly developed Karabo software. Graphical user interfaces to control each subsystem are available and can easily be reconfigured using the jDDD toolkit [16]. A vast suite of high-level control software integrates and automates more complex tasks like emittance measurement and optics matching. The readiness of the control software upon start-up was one of the key preconditions for the fast success of the commissioning.

Linac Commissioning

The commissioning of the XFEL accelerator started mid of January 2017. The effort was planned sequentially with the general goal to establish beam transport to subsequent sections as early as possible. The number of bunches has been kept low (<30) to lower the beam power in the initial phase of the commissioning.

LLRF commissioning was given highest priority. As of summer 2017, 22 of the 24 RF stations in the linac are available. For each of the RF stations a sequence of steps had to be performed [17]. Frequency tuning, RF signal checks, coupler tuning, coarse power-based calibration and closed-loop operation was achieved without beam, and after establishing beam transport (typical 30 bunches, 500 pC) cavity phasing and beam-based calibration followed. While the first station in L1 needed one week of commissioning, the three stations of L2 could be handed over to operations after only another week. Work in L3 then progressed in parallel on all available stations. The possibility to time shift the RF pulse of stations with respect to each other allowed parallel operation of stations on or off the beam and thus simultaneous beam commissioning. The RF commissioning went extremely smooth. Multi-pacting was observed at almost all RF stations at an accelerating gradient of 17-18 MV/m but could be conditioned in all cases with an effort of a couple of hours per station.

The phase and amplitude stability was measured inner loop to be better than 0.01° and 0.01%. Preliminary beam energy jitter measurements give an upper limit for the RMS relative energy jitter of 3e-4 after BC1 and 1e-4 after BC2. The measured energy stability at the linac end is a factor 4 better than the specified 0.01%.

At present all stations perform at about 80% of the gradient limit obtained from previous module test results [18, 19]. Further fine-tuning of the regulation loops together with explicit verification of the individually tailored waveguide distribution will increase this in the future. The maximum energy reached so far with all available stations on the beam is 14 GeV which is the energy envisioned for first user operation.

Beamline commissioning could be performed in parallel to the LLRF commissioning, with the first beam transported to the beam dump after the linac by end of February. Trajectory response measurements proved very useful in validating the optics model and were possible right from 'Day 1' due to the excellent performing BPM system. Also other diagnostic devices like screens, toroids, beam-loss-monitors, dark current monitors were available from the beginning [20]. The BPM resolution exceeds expectations with sub-micron resolution for the cavity BPMs.

Longitudinal diagnostics commissioning is ongoing. The transverse deflecting structure after the last bunch compressor allowed beam length measurements down to about 170 fs FWHM (resolution limited). Bunch compression monitors (BCM) based on diffraction radiation allow relative bunch length measurements for shorter bunches and thus setting up bunch compression for the design 5 kA. The BCM is used in a slow feedback loop to stabilize the peak current. Newly developed beam arrival

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monitors will become available soon [21, 22]. Compression factors during initial operation are set to up to 200.

Transverse beam sizes are measured with scintillating screens (LYSO) observed under an angle of 90 deg. Resolution of the screens is measured to be of the order of a few µm [23]. Typical transverse beam sizes to be resolved range from 40 to 100 µm, and are thus well above the resolution limit of the screens. Nevertheless, emittance measurements give unreasonable results at small beam sizes below about 50 µm, as they appear in the higher energy four-screen sections after BC1, BC2 and L3. Only multi-quadrupole scans with enlarged beta-functions at the screen position give reliable results. This effect is under investigation [24].

Beam Transport through SASE1 / First Lasing

After obtaining the operation permission for the 'North Branch' beam distribution on April 26, first beam was transported through the 1 km long beam transport line the next day. Moderate energies (10.4 GeV) were used together with a reduced 1 Hz repetition rate. The 8.8 mm by 8 mm inner aperture undulator vacuum system with a length of 235 m (SASE1) resp. 150 m (SASE3) was passed without any additional steering and moderate trajectory amplitudes of 1 mm peak. A day later all 35 undulator segments were closed to 11 mm gap ($k = 3.5$) and the phase shifters could be adjusted to the settings obtained through magnetic measurements [25].

First lasing was observed on May 2nd after some empirical tuning of the compression and the undulator trajectory. At a further reduced energy of 6.4 GeV and an undulator k of 3.5 the radiation wavelength was about 9 Å. At this moment only a fluorescent screen (25 mm by 32 mm wide YAG) was available at the beginning of the photon beamline about 170 m downstream of the last SASE1 undulator segment. Nevertheless, already spontaneous radiation from even one single undulator segment could be observed by an increase of the overall emitted light intensity.

LASING AT 2 ÅNGSTRÖM AND BELOW

Further steps to lase at shorter wavelength were required. In a common effort of both, the electron and the photon beam commissioning team, beam based alignment and more systematic tuning of longitudinal and transverse bunch properties were carried out while more and more photon beam diagnostic came into operation.

First lasing at 2 Ångström was achieved on May 24th, and only three days later an energy of 1 mJ close to saturation was reached (see Fig. 4). Further optimization including the training of new machine operators was possible since the authorization to inject photon beam into the SASE1 experimental hutch was only given June 21.

The X-ray beam was successfully guided via the respective mirrors into the experiment hutches, where a number of highly specialized instruments for characterizing the properties of the X-ray beam were meanwhile commissioned.

Directly after the first X-ray beam was guided into the hutches on 23 June, teams at European XFEL started with the characterization of the beam and started experiments for the commissioning of the instruments.

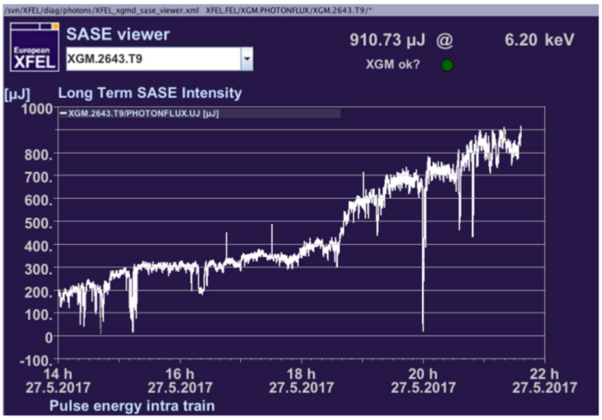

Figure 4: Long term SASE intensity measured at 2 Ångström wavelength.

One of the first diffraction patterns from European XFEL was recorded through an approximately millimeter-wide square gap at the SPB/SFX instrument (see Fig. 5). The evenly spaced, grid-like lines of the pattern show areas of interference resulting from diffraction through the gap, demonstrating that the light has very high quality laser-like properties.

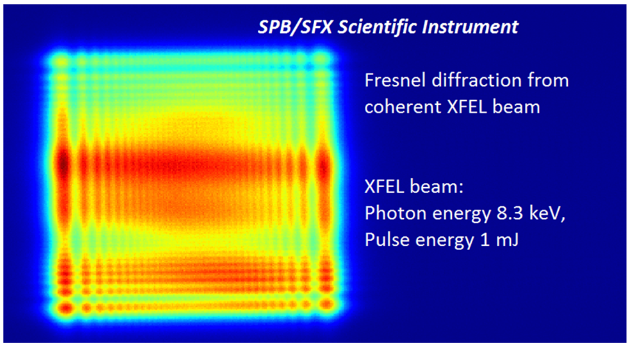

Figure 5: One of the first diffraction patterns from European XFEL. Credit: European XFEL

With a wavelength of initially two Ångström and the required peak light intensity, the X-ray light will allow the recording of atomic detail. At two experiment stations first experiments are now possible: At the instrument FXE (Femtosecond X-ray Experiments), that is designed for the research of extremely fast processes, and at the instrument SPB/SFX (Single Particles, Clusters, and Biomolecules / Serial Femtosecond Crystallography), designed for studying biomolecules and biological structures.

OUTLOOK

The European XFEL accelerator has been put into initial operation. In comparison with the published commissioning schedule, major commissioning targets were achieved ahead of time. The initial accelerator operation is smooth, the chosen superconducting technology is convincing. The series production as well as the recent commissioning of many challenging accelerator subsystems were successful. The European XFEL is one of the worldwide visible large scale research facilities. We are looking forward to hosting highest quality user experiments with major impact on science.

First user experiments are scheduled for September 2017. In parallel the accelerator will be further developed towards higher energies and beam power. Commissioning of SASE3 and SASE2 will complete the experimental possibilities of the facility in 2018. Full operation with 4,000 user hours per year is foreseen in 2019.

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