COMMISSIONING OF THE EUROPEAN XFEL ACCELERATOR*

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Abstract

The European XFEL uses the world's largest superconducting RF installation to drive three independent SASE FELs. After eight years of construction the facility is now brought into operation. First 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 3 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 2700 bunches per pulse. Electron beams will be distributed to the 3 different beamlines within a pulse, thus being able to operate three experiments 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 CNRS/IN2P3 (Orsay, France), CEA/IRFU (Saclay, 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), 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; and the commissioning of the linear accelerator began end of 2016.

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 occupies the lowest level of a 7 stories underground building that also serves as the entry shaft to the main linac tunnel. Next access to the tunnel is about 2 km downstream at the bifurcation point into the beam distribution lines. The beam distribution provides space for 5 undulators (3 being initially installed), each feeding a separate beamline so that a fan of 5 almost parallel tunnels with a distance of about 17 m enters the experimental hall 3.3 km away from the electron source.

The European XFEL photo-injector consists of a normal-conducting 1.3 GHz 1.6 cell accelerating cavity [4]. A Cs2Te-cathode is illuminated by a Nd:YLF laser operating at 1047 nm and converted to UV wavelength in two conversion stages.

The photo-injector is followed by a standard superconducting 1.3 GHz accelerating module and a 3rd harmonic linearizer, consisting of 3.9 GHz module – also superconducting – containing eight 9-cell cavities. A laser-heater, a diagnostic section and a high-power dump complete the injector.

A three-stage bunch compression scheme is used to reduce both micro-bunching and the required 3.9 GHz voltage. 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). Diagnostic stations are placed after the second and third compression stage.

Figure 1: First bunch compression chicane.

The superconducting linear accelerator consists of 96 TESLA type accelerator modules. Always 4 modules are fed by one 10 MW multi-beam klystron. 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.

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

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After the linac a collimation section protects downstream hardware in case of component failure and collimates halo particles [5].

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 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. Figure 3 summarizes the accelerator layout.

Electron bunch charges are planned to be variable from 20 pC to 1000 pC [6], with resulting bunch length after compression ranging from 3 fs to 150 fs FWHM [7]. 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.

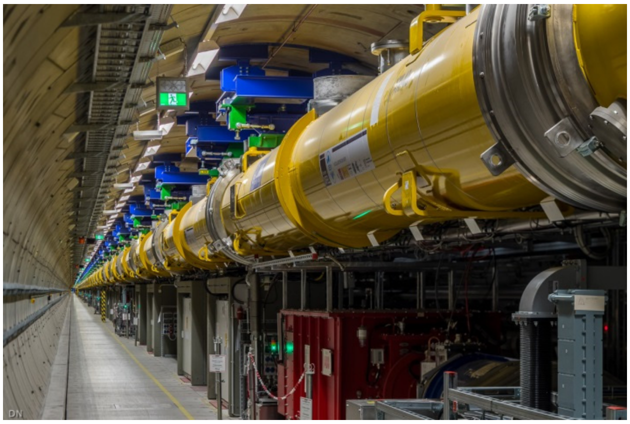

Figure 2: View into the linac tunnel with the accelerator modules suspended from the ceiling and the RF infrastructure placed below, on the floor.

COMMISSIONING RESULTS

Injector Commissioning

The injector can be operated in a separate radiation enclosure independent of the remaining tunnel installations.

The beam dump at the end of the injector allows operating the injector up to full beam power.

The XFEL photoinjector has been conditioned at PITZ, the photoinjector test stand at DESY, Zeuthen [8, 9]. RF operation in the design configuration in the XFEL injector tunnel took place in December 2013 [10] and first electrons where produced in installation breaks in 2014 and 2015.

The superconducting accelerator of the injector was cooled down in December 2015 and first electrons were accelerated to 130 MeV on Dec. 18th [11]. Also at that early stage the 3rd harmonic lineariser was commissioned and operated at the design gradient throughout the complete run [12]. 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 (see Table 1).

Most notable are the extensive emittance studies that were made possible by a 4-off-axis-screen measurement stage. This enables fast parameter scans and the study of the emittance evolution along long bunch trains [13]. This method can even be combined with a transverse deflecting structure, thus giving information about the slice properties along the bunch train. It could be shown that with proper tuning of the laser pulse and the RF parameters the emittance and optical functions can be kept constant.

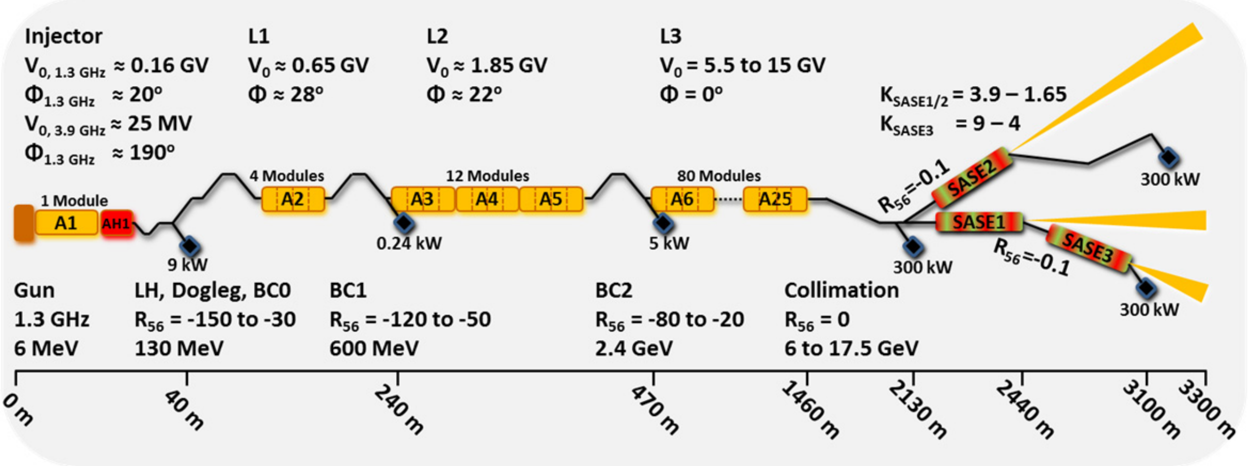

Figure 3: Schematic overview of the European XFEL accelerator. Single RF stations are named A*nn* and feed either one module (A1) or 4 modules (A2-A25). R_{56} ranges for the bunch compressors are given in mm, and the phases of the different linac sections refer to typical compression set-ups. The maximum 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.

Commissioning of the laser heater has been progressed up to the point that transverse and longitudinal overlap can be established and an increase of the energy spread has been observed [14].

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 [15]. Initially the XFEL is thus operated with a slightly reduced injector cavity gradient.

Table 1: Injector Parameters

Parameter	Design	Achieved
RF pulse rep. rate [Hz]	10	10
RF flat top [µs]	650	650
Bunches/RF pulse	2700	2700
Bunch charges [pC]	20-1000	20-1000
Proj. emittance @ 500 pC [mm mrad]		1.2
Slice. emittance @ 500 pC [mm mrad]	0.6	0.6[1]

Cryogenic System

The European XFEL cryogenic system consist of two overhauled strings of the HERA cryo-plant, a new distribution box and transition line to the XFEL accelerator entrance shaft, cold compressors to reach 2K and further distribution boxes to distribute the He towards the injector, and finally the long uninterrupted cryo-string of the linear accelerator together with its transfer and bypass-lines. The cooling power was measured during the pre-commissioning to be > 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, all exceeding specifications. Cool down of the linac from room-temperature to 4 K was achieved within 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%.

Electronics and Control System

The front end electronics for LLRF, high-power RF, beam diagnostics, vacuum and cryo-control is installed in shielded racks in the tunnel. The newly developed MTCA.4 standard is used throughout the installation [16, 17]. About 250 crates in the tunnel benefit from the enhanced remote monitoring and maintenance capabilities, thus reducing the need for time-consuming on the spot interventions to a minimum.

The accelerators 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 re-configured using the jDDD toolkit [18]. 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 began mid of January after the initial tests of the cryo-plant were finished and the official operation approval was obtained. The commissioning effort was planned as a series of sequential steps with the general goal to establish beam transport to subsequent sections as soon as possible. The number of bunches has been kept low (<30) to lower the beam power in the initial phase of the commissioning.

Table 2 summarizes the parameters that have been achieved during the commissioning.

LLRF commissioning was given highest priority. At this time 19 of the 24 RF stations in the linac are available. For each of the RF stations a sequence of steps had to be performed [19]. 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 another week. Work in L3 then progressed in parallel on all 15 available stations. The possibility to time shift the RF pulse of stations with respect to each other allowed the parallel operation of stations on or off the beam and thus simultaneous beam commissioning. The RF commissioning went smoothly. 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 the injector and 1e-4 at BC1 and BC2.

At present all stations perform at about 80% of the gradient limit obtained from previous module test results [20]. It is expected that further fine-tuning of the regulation loops will increase this in the future. The maximum energy reached so far with all available stations on the beam is 12 GeV, adding three more stations in the near future will enable the 14 GeV operation envisioned for first user experiments.

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

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[1] Measured with the 4 screen method. Measurements with multi-quad scan method show emittances as low as 0.4 mm mrad.

ISBN 978-3-95450-182-3

Table 2: European XFEL design parameters and target parameters for the initial commissioning together with the values achieved as of beginning of May 2017.

Parameter		Design	Linac Commissioning Target	Achieved
Energy	GeV	17.5	14	12
Bunch Charge	pC	20-1000	500	100-500
Macro Pulse Repetition Rate	Hz	10	10	10
Macro Pulse RF length	µs	600	600	600
Inner pulse bunch frequency		1-2700	1-60	1-30
Max. beam power at linac end	kW	473	4.2	1.8
Peak Current	kA	3-5	5	5
Compression Factor		200-2000	200	200

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 immediately [21]. 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 240 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 monitors will become available soon [22, 23].

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 [24]. 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 and BC2. Only multi-quadrupole scans with enlarged beta-functions at the screen position give reliable results. This effect is under investigation.

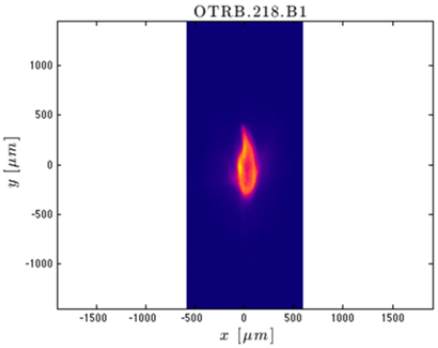

Figure 4: Transverse beam projection on a scintillating screen after bunch compressor BC1.

At almost all screen stations along the beamline a ring like structure can be observed in the transverse projection (see Fig. 4). Comparable phase space distributions can be obtained in simulations assuming a transverse laser profile that is sharply truncated – as is the case for the photoinjector laser. Observability of these structures should depend strongly on phase advances; but this is not the case. In fact the structure is visible even after compression and acceleration. Further studies will follow [25].

BEAM TRANSPORT THROUGH SASE1 AND 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 at moderate energies (10.4 GeV) and 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) were 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 [26].

At present 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. Spontaneous radiation from even one single undulator segment could be observed by an increase of the overall emitted light intensity.

At long photon wavelength the expected gain length for ≈ 1 mm mrad slice emittance is in the order of a few meters. Thus one would expect exponential gain even without a proper aligned undulator trajectory. First lasing was observed on May 2nd after some empirical tuning of the compression and the undulator trajectory (see Fig. 5). At an energy of 6.4 GeV and an undulator k of 3.5 the radiation wavelength was about 9 Å.

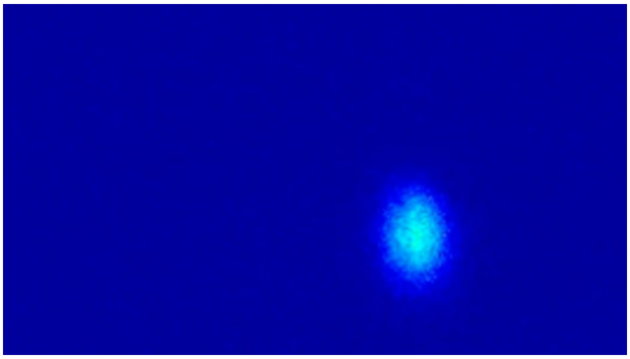

Figure 5: Screen shot of the SASE signal observed on a YAG screen about 170 m downstream of the last undulator.

Further steps to shorter wavelength will require beam based alignment (ongoing) and more systematic tuning of longitudinal and transverse bunch properties.

OUTLOOK

The European XFEL accelerator has been put into initial operation reaching the commissioning targets ahead of time. In the near future the photon beamline and diagnostics commissioning will start with the goal to deliver first beam to the SASE1 experiment hutch in early summer. 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 4000 user hours per year is foreseen in 2019.

ACKNOWLEDGEMENT

The European XFEL is a joint achievement of many people working in different parts of the project. The Authors wish to thank all of them for their long lasting devotion and enthusiasm. In addition we would like to acknowledge the help of staff from CANDLE, ELETTRA, PSI, and SLAC during the commissioning.

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