First operation of a MHz-repetition-rate hard X-ray free-electron laser driven by a superconducting linear accelerator

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Abstract

The European XFEL is the first hard X-ray free-electron laser (FEL) based on a high electron energy superconducting linear accelerator. The superconducting technology allows for the acceleration of many electron bunches within one radio-frequency pulse of the accelerating voltage and, in turn, for the generation of a large number of hard X-rays pulses. We report on the first operation of the European XFEL accelerator with up to 5000 electron bunches per second and demonstrating full energy of 17.5 GeV. Feedback mechanisms enable stabilization of the electron beam delivery at the FEL undulator in space and time. The measured FEL gain curve at 9.3 keV is in good agreement with predictions for saturated FEL radiation. Hard X-ray lasing was achieved between 7 keV and 14 keV with pulse energies of up to 2.0 mJ. Using the high repetition rate, a 6 W average power FEL beam was created.

Introduction

Hard X-ray free-electron lasers (FELs) have been proposed and established as light sources for X-ray research over the last decade [1-5]. The successful design, construction, and operation of these facilities is based on theoretical, experimental, and technological developments in FEL and accelerator physics starting from the early 1980s until now (see review papers [6–8] and references therein). Seminal studies refer to the generation of X-ray radiation by an electron beam during a single pass of an undulator where the amplification process develops from the shot noise in the electron beam [9–11] (later on, this amplifier configuration was named a self-amplified spontaneous emission (SASE) FEL [13]). Starting from 1998, we observed a very rapid development of SASE FEL facilities operating in the infrared range (VISA experiment in 1998 [14]), visible (LEUTL, 2000 [15]), and soft X-ray (FLASH, 2000, [16]), with the first X-ray user facility, Free Electron LASer in Hamburg (FLASH) put into operation in 2005 [17].

The completely new capabilities of these facilities and the enormous scientific success are driving a huge demand for access, which can be partly responded to by high repetition-rate facilities serving several scientific instruments in parallel. The European X-Ray Free-Electron Laser Facility (European XFEL) is an international research infrastructure built in the Hamburg region of Germany. Twelve nations have contributed to its construction (Denmark, France, Germany, Hungary, Italy, Poland, Russia, Slovenia, Spain, Sweden, Switzerland, and the United Kingdom). The European XFEL accelerator is based on superconducting technology developed in the framework of the TESLA collaboration by an international consortium centred around Deutsches Elektronen-Synchrotron (DESY) [18]. After observation of first lasing in the VUV regime at the Tesla Test Facility (now FLASH) [16], a hard X-ray FEL was proposed as part of a linear collider and later transformed into a stand-alone facility [19]. The realization of the project as an international research infrastructure [4] started officially in 2009 with the foundation of the European XFEL GmbH and the start of civil construction.

The complete facility is constructed underground about 6 to 38 m below the surface level, in several 4.6 and 5.3 m diameter tunnels with a total length of about 5.3 km (see Fig. 1). The 50 m long injector occupies the lowest level of a seven-storey underground building that also serves as the entry shaft to the main linear accelerator (linac) tunnel. The next access point to the tunnel system is about 2 km downstream at the bifurcation point into the beam distribution lines. The beam distribution provides space for five FEL undulators (three having been initially installed), each pointing into a separate tunnel, so that a fan of five almost parallel tunnels with a lateral distance of 17 m between beams enters the experiment hall 3.3 km from the electron source. The civil construction of the tunnels ended in 2013, and infrastructure installation lasted until 2014. By the end of 2016, the accelerator installation was complete (Fig. 2) and its commissioning and operation started. Installation of photon components and experiment setup proceeded beamline by beamline, with the first completed in summer 2017. First experiments of user groups started in September 2017, leading to initial scientific results [20], [21]. Installation of the second and third beamlines was completed in the summer and autumn of 2018, respectively.

The European XFEL uses the SASE FEL principle where radiation is produced by the electron beam during a single pass of an undulator [9], [10], [11]. The amplification process develops from the shot noise in the electron beam, and strong, coherent, narrow band radiation is generated near the resonant wavelength $\lambda=\lambda_w(1+K^2)/(2\gamma^2)$, where γ is the relativistic Lorentz factor, λ_w is the undulator period, $K=eH_w\lambda_w/(2\pi mc)$ is the undulator parameter, H_w is the rms on-axis magnetic field strength of the undulator, c is the speed of light, and m and e are mass and charge of the electron. The main characteristics of the X-ray FEL (the field gain length L_g, saturation length L_{sat}, saturation efficiency $\eta=W_{rad}/W_{eb}$, coherence time at saturation τ_c, and spectrum bandwidth σ_ω) are well estimated in terms of the FEL parameter ρ and the number of cooperating electrons $N_c=I/(e\rho\omega)$ [12], [22], [23]:

$$L_g \sim \frac{\lambda_w}{4\pi\rho}\ ,\ L_{sat} \sim \frac{\lambda_w}{4\pi\rho}\left[3+\frac{\ln N_c}{\sqrt{3}}\right],\ |\eta \simeq \rho|\ ,\ \tau_C \simeq \frac{1}{\rho\omega}\sqrt{\frac{\pi \ln N_c}{18}}\ ,\ \sigma_\omega = \sqrt{\pi}/\tau_c.$$

The FEL parameter ρ is given by [12]: $\rho = \left[\lambda_w^2 j_0 K^2 A_{jj}^2/(16\pi I_A \gamma^3)\right]^{1/3}$, where j_0 is the beam current density, $I_A = mc^3/e \simeq 17$ kA is Alfven current, and A_{JJ} is a coupling factor with a value close to 1. The typical amplification bandwidth of the X-ray FEL is of the order of 0.1%. The electron beam in an X-ray FEL transfers enormous peak power. For typical X-ray FEL parameters (electron energy of 17.5 GeV, peak current of 5 kA, and bunch charge of 0.5 nC), the peak power in the electron beam W_{eb} is about 100 TW, and the kinetic energy of electrons is about 10 J. The conversion efficiency of kinetic energy of electrons to the light is of the order of the amplification bandwidth; thus, the peak power of X-ray radiation W_{rad} is in the multi-GW range, and radiation pulse energies are in the few mJ range.

The unique feature of the European XFEL is the capability of the superconducting linac to accelerate trains of many (up to 2700) electron bunches within one 600 µs long radio-frequency (RF) pulse. Using a 10 Hz RF pulse repetition rate, up to 27000 electron bunches, and thus photon pulses, can be produced each second. The working point for the pulsed superconducting linac is optimized in terms of pulse duration, accelerating gradient, and cryo load. Future projects [24], [25] aim for continuous wave operation and thus an equidistant bunch structure. This is possible through recent advances in the treatment of superconducting cavities but will nevertheless come at the price of reduced accelerating gradient and increased cryogenic load.

Electron bunch charges can be varied from 20 to 1000 pC [26], with resulting bunch lengths after compression ranging from 3 to 150 fs FWHM [27]. With different linac energies ranging from 8 to 17.5 GeV and variable gap undulators, photon energies from 0.25 to 25 keV can be covered. A sophisticated electron-bunch distribution system allows to distribute bunches into each undulator beamline individually, thus enabling the simultaneous operation of several experiments.

Here we report on the first operation of the European XFEL with up to 5000 bunches/second at an electron energy of 14 GeV, serving the SASE1 undulator and producing SASE FEL radiation at around 9 keV.

Results

Injector

The photo-injector consists of a normal-conducting 1.3 GHz 1.6 cell cavity [28] with a Cs_2Te photocathode inserted at the back plane, which is illuminated by a Nd:YLF laser operating at 1047 nm and converted to UV wavelength in two conversion stages. The laser was provided by the Max Born Institute, Berlin, Germany. A second laser was constructed as a backup with reduced specifications with respect to the achievable pulse length. This laser is presently used as the primary injector laser because of its capability to be connected to the optical synchronization system, leading to a higher timing accuracy during operation. The photo-injector has been conditioned and characterized at the Photo Injector Test

Facility at DESY in Zeuthen (PITZ), where a projected normalized emittance of 0.4 mm mrad has been demonstrated at a bunch charge of 500 pC [29]. This was achieved at the design cavity gradient of 60 MV/m, or, taking into account the required high duty cycle, at an average power of 60 kW. The photo-injector was operated at a reduced gradient between 52 and 58 MV/m at the European XFEL in order to enhance availability during commissioning and early operation.

The photo-injector is followed by a superconducting 1.3 GHz accelerating module and a third harmonic linearizer, consisting of a 3.9 GHz module—also superconducting—that contains eight 9-cell cavities [30]. A laser-heater [31], a diagnostic section, and a high-power dump complete the injector. The diagnostic section allows measuring projected and slice emittance along the bunch train. This is achieved by a combination of a transverse deflecting cavity and several kickers and screens [32]. The transverse deflecting cavity deflects electrons within a bunch differently, depending on their longitudinal position. This allows measuring the transverse emittance of individual bunch slices. The longitudinal dimensions of the bunch are determined from the projection of the deflected bunch profile, and slice energy spread can be measured in a dispersive beamline before the electron beam dump.

With the given setup, projected emittances of 1.2 mm mrad (compared to the specified 1.5 mm mrad) and slice emittances of 0.6 mm mrad were observed. Most notable is the capability to also measure beam parameters along the bunch train, which helps to set up equal lasing conditions along the bunch train [33].

Bunch compression

A three-stage system for bunch compression is used, separating the linac into three parts called L1, L2, and L3 (compare Fig. 3). All magnetic chicanes are tunable within a wide range to allow for flexible compression scenarios, for instance balancing peak current and arrival time stability with accelerator performance. Tuning is achieved by means of large pole width dipole magnets and accordingly wide (400 mm) vacuum chambers. Diagnostic stations similar to the one in the injector are placed after the second and third compression stage.

During first operation in 2017, the accelerator was run at a bunch charge of 500 pC. The bunch length measurement was resolution-limited at that time, and the bunch length was estimated to be of the order of 50 fs rms. Starting with 2018, the bunch charge was reduced to 250 pC, and functional bunch length measurements confirmed the simulated pulse duration of about 20 fs (rms, gaussian fit) (compare Tab. 1).

Accelerator

The superconducting linac consists of 96 accelerator modules built in TESLA technology. Groups of four modules, with eight 9-cell cavities each, are fed by one 10 MW multi-beam klystron. The accelerator modules are suspended from the tunnel ceiling (compare Fig. 2), while the complete RF infrastructure (klystrons, pulse transformers, and 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 transformers by up to 2 km long cables.

After the linac, a collimation section protects downstream hardware in case of component failure and collimates halo particles [34].

The electrons are distributed by a fast rise-time, high precision, flat-top strip-line kicker into one of the two electron beamlines. Another kicker system, installed upstream, is capable of deflecting single bunches into a dump beamline [35]. This configuration allows for a free choice of the bunch pattern in each electron beamline, while operating the linac with constant beam loading. Fig. 3 summarizes the accelerator layout.

Commissioning of the RF system was given highest priority in the early phase of the linac operation. The proper adjustment of the many parameters of the so-called “low-level RF” (LLRF) system—stabilizing the acceleration field’s amplitude and phase within each RF pulse and from pulse to pulse—was achieved in a sequence of steps that had to be performed for each of the 25 RF stations [36]. Frequency tuning, RF signal checks, coupler tuning, coarse power-based calibration, and closed-loop operation were achieved without beam. After establishing beam transport, typically 30 bunches at 500 pC, cavity phasing and beam-based calibration followed. While the first station in the linac section L1 needed one week of commissioning, the three stations of L2 could be handed over to operations after only one more 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 the parallel operation of different stations for beam acceleration and RF commissioning, thus increasing the available accelerating field steadily during beam commissioning.

After the initial commissioning, each station has been fine-tuned to obtain maximum performance, which is at present at about 90% of the gradient limit obtained from previous module test results [37]. The maximum energy reached with all available stations on the beam is 17.5 GeV so far, in accordance with the design specification. User runs have been performed with 14 GeV, thus giving ample overhead for reliable linac operation.

The phase and amplitude stability of the RF pulse is measured within the RF regulation loops to be better than 0.01 deg and 0.01% [38] and thus exceeds the specifications.

Measurements of the electron energy jitter give an upper limit for the RMS relative energy jitter of 3×10^{-4} after the injector, 1.5×10^{-4} after BC1 and BC2, and 1×10^{-4} after the accelerator. The arrival time jitter is measured [39] to be about 20–30 fs RMS after the last bunch compression stage. Energy stability and arrival time are not affected by further beam transport to the undulators, and the above values thus represent the stability to be expected at the FELs.

FEL undulators

The SASE1 FEL system consists of 35 undulator segments of 5 m length interspaced by 1.1 m sections with air coils, permanent magnet phase shifters, quadrupole magnets, and electron beam position monitors (BPMs), with a total length of 213.5 m (see Fig. 4). The 40 mm period undulators are gap-tunable within a range of 10–220 mm, with an operational gap range of 10–20 mm, to enable selecting the photon energy for a given electron energy. Parameters of the SASE1 FEL undulator system are found in Table 1.

The undulator segments and phase shifters were assembled, tested, and tuned prior to installation in the tunnel. All magnetic parameters were tuned using pole height tuning [40]. Permanent magnet phase shifters are installed in between undulator segments to match the phases of the electron motion and FEL radiation field. Combining the data of undulator segments and phase shifters allows determination of the gap of a specific phase shifter for the selected *K* parameter of the undulator as a function of the two surrounding undulator segments [41].

A particular requirement for successful FEL lasing using gap-tunable undulators is the straightness of the electron orbit for all undulator *K* values. The phase shifters are designed to have very low stray magnetic fields and first field integral errors [42], [43]. In order to compensate for the total first and second field integrals of each undulator segment, each segment is equipped with a combined horizontalvertical air coil at either end [44]. Air coil currents were determined by moving wire measurements with an accuracy better than 0.004 Tmm and 20 Tmm^2, respectively [45]. While the air coils compensate residual gap-dependent field integral errors of the undulator segments, the overall electron trajectory is controlled by moveable quadrupoles (QMs). Both air coils and QMs provide steering free of magnetic hysteresis.

The controls of the FEL undulator system use lookup tables to synchronize the phase-shifter gap and the four air coils with the gap of each of the undulator segments. Selection of the K parameter is based on the tabulated gap vs. the K values: The gaps were measured with a typical accuracy of ±1 μm or better. For a requested K, the gap can be adjusted such that the resulting ΔK/K over all segments of the system is less than 10^{-4}. For each K value, the required phase shifter gap and proper air coil currents are also taken from the lookup table. The contents of these lookup tables were initially determined through laboratory measurements of the undulator fields. Further refinement and updating using beam-based data led to further improvements.

Photon beam properties

The first lasing of SASE1 at 1.3 keV was observed during commissioning at an electron beam energy of 6.4 GeV and a value of the undulator *K* parameter of about 3.5. The estimated field gain length for these parameters is below 2 m, and thus the alignment of the electron trajectory was relaxed. Lasing was demonstrated by detecting an increase of the integrated intensity on a scintillating screen about 170 m downstream from the undulator when changing the electron peak current [46].

Crucial for lasing is the overlap of the electron trajectory with the radiation field. At wavelength in the hard X-ray regime (above 7 keV), this requires the straightness of the trajectory to be within a few microns along several of the 6.1 m long undulator cells. These tolerances cannot be achieved by standard alignment and have to be obtained by beam-based methods. Several photon or electron beam–based techniques exist. We have chosen a method based on observation and correction of electron trajectories at different electron energies (electron beam–based alignment (eBBA)) [47], [3]. The initial eBBA resulted in a correction of the quadrupole centre and beam position monitor positions of the order of 0.5 mm peak-to-peak as had been expected for the alignment of the 213.5m long undulator system.

In addition to the electron trajectory, the K value profile along the undulator (taper), the phase shifter gap, and the air coil settings at present need to be adjusted empirically to maximize FEL intensity. Some of these time-consuming adjustments will be replaced by photon-based methods after the needed diagnostics are fully commissioned.

Photon pulse energies of up to 2 mJ between 7 and 14 keV have been achieved. The high pulse energies were reached using tapering of undulator segments.

To characterize the FEL radiation, several photon diagnostics and optics devices were used [48], [49], [50]: screens for imaging spontaneous and FEL radiation, slits for collimating spontaneous radiation, and attenuators. The absolute FEL pulse energy is measured in a calibrated ionization chamber (X-ray gas monitor (XGM)) at 185 m behind the undulator. The calibrated signal is an average over several pulse trains; however, the monitor is also capable of providing the shot-to-shot pulse energies at a 4.5 MHz repetition rate within trains. At pulse energies below approx. 50 μJ, the XGM sensitivity is not sufficient to perform absolute measurements, but relative changes can be monitored down to the low level of spontaneous radiation of single undulator segments, which is essential for tuning for SASE lasing.

Relative pulse energy measurements can also be obtained from calculating the integrated intensity on imagers.

An example of this measurement as a function of magnetic length of the undulator is given in Fig. 5 for a photon energy of 9.3 keV. The 14 GeV electron beam had nominal parameters of 250 pC bunch charge, 5 kA peak current, and a normalized slice emittance of about 0.6 mm mrad. Start-to-end beam dynamics simulations suggest a saturation length of about 80 m and an FEL pulse energy of about 600 μJ at these parameters. The measured gain curve clearly demonstrates a stage of exponential amplification and a saturation regime. The measurement yields a saturation length of about 100 m and radiation pulse energy comparable with predictions. Some 20% overhead of the saturation length is explained by practical difficulties of optimization of the FEL process at the initial stage of amplification at low pulse energies. Analysis of the photon beam images (see inset in Fig. 5) indicates that spatial properties of the radiation are in good agreement with FEL simulations based on measured values of the electron beam emittance. The measured FEL radiation properties demonstrate reasonable agreement with predicted baseline parameters [51]. However, we still observe that the fluctuation of the radiation pulse energy is mainly driven by jittering accelerators parameters. The nature and source of jittering is under study, and we believe that proper tuning of all systems of the superconducting accelerator will allow reducing fluctuations to the level of fundamental fluctuations, as has been demonstrated at FLASH [52].

Fig. 6 shows the measurement of the SASE spectrum taken with the High REsolution X-ray (HiREX) single-shot spectrometer using a Si111 crystal in 333 reflection with a bending radius of 75 mm and yielding a resolution of 250 meV and a resolving power of 3.74×10^4 [53]. The HiREX is installed in the photon transport system behind a pair of X-ray offset mirrors. The measured FEL bandwidth is around 0.3% FWHM, more than twice the nominal Pierce parameter for the given machine settings (14 GeV, 500 pC, 5 kA). This broadening is not caused by electron energy jitter but is rather an indication of energy chirp in the electron beam, leading to a frequency chirp in the SASE radiation pulse.

One of the biggest asset of the European XFEL is the capability to accelerate a large number of electron bunches per RF pulse yielding a train of up to 2700 photon pulses. A test run with up to 500 bunches per RF pulse has been performed. The relative electron energy variation over such a pulse train is about 0.01% and is ensured by proper adjustment of the LLRF parameters. In addition, a fast transverse intra-bunch train feedback system corrects residual trajectory variations within a bunch train to better than 3 µm peak-to-peak [54]. This system is also capable of correcting the pulse-to-pulse transverse jitter within the same boundaries, yielding a transverse jitter of electron beam position and pointing of about 1/10 of the electron beam size. An example of the SASE1 FEL results is shown in Fig. 7, where a screen shot of the XGM data panel shows the distribution of pulse energy over a train of 500 X-ray pulses, with a total duration of 125 µs. The measured pulse energy values correspond to an average X-ray FEL power of 6 Watt at 9.3 keV, or even 4.8 kW throughout the X-ray pulse train. Bunch-to-bunch fluctuation of the FEL pulse energy is always expected, due to the statistical nature of SASE radiation. In addition, some modulation of the pulse energy over the train can be observed, which is attributed to very small differences of the bunch properties (energy, longitudinal profile, and trajectory) within one bunch train.

In summary, we have shown commissioning and operation results from the electron accelerator and first SASE FEL source of the European XFEL, the first high-repetition-rate hard X-ray FEL facility. Already during this early operation of the superconducting accelerator, many target parameters have been achieved, such as full electron energy of 17.5 GeV or operation of the FEL at repetition rates of up to 4.5 MHz. Furthermore, the feedback mechanisms enabled by the operation of electron bunch trains provide a gain in stability of beam position and arrival. The FEL radiation properties obtained from the first operated SASE FEL are in good agreement with predictions of the saturated FEL radiation. Using the tapering of additional undulator segments beyond the saturation point, it becomes possible to significantly increase the FEL pulse energy. At a photon energy of 9.3 keV, using 500 bunches at 4.5 MHz per bunch train, and an average pulse energy of approx. 1.5 mJ, a 6 W hard X-ray FEL has been produced. First user experiments have been performed, albeit at a reduced number of pulses per second.

Fig. 1: Bird's-eye view of the facility showing the location of the tunnel buildings in the urban area of the city of Hamburg. The injector is on the right on the DESY campus, while the experiment hall and headquarters of the European XFEL are on the left in the federal state of Schleswig-Holstein. Note the fan of five photon beamlines entering the experiment hall.

Fig. 2: View along the almost 1 km long superconducting linac section L3, which accelerates the beam after the last bunch compression stage from 2.5 GeV up to 17.5 GeV. Note that the accelerator is supported from the tunnel ceiling, while the complete infrastructure (high-power RF, electronics, and auxiliaries) is installed on the tunnel floor for easy maintenance and access.

Fig. 3: Schematic layout of the European XFEL accelerator and photon beam transport as used in the first lasing and initial operation phase.

Fig. 4: View of the undulator installation in the tunnel. A 5 m long undulator segment is shown in front, while the 1.1 m intersection with the BPM, quadrupole magnet, and phase shifter is partially hidden from view on the right side of the undulator. During operation, the complete undulator is enclosed in climate housing. Panels of the removable housing can be seen to the far right.

Fig. 5: The integrated FEL pulse energy as a function of the undulator magnetic length measured by the transparent X-ray gas monitor device (XGM, red) and the invasive FEL imager (blue). For the FEL imager, a summed image of ~1500 trains is used for each undulator length (the inset shows a single image for 100 m undulator length). The XGM value is averaged over all trains. The FEL imager values are normalized to the XGM value at an undulator length of 90 m.

Fig. 6: The SASE spectrum measured by the HiREX single-shot spectrometer. The top figure shows the single-shot spectra collected at 9.36 keV with an electron energy of 14 GeV and 500 pC bunch charge. The bottom figure shows the line profile of the above spectrum.

Fig. 7: SASE FEL pulse energy measured for each X-ray pulse of a train of 500 bunches. The measurement error is indicated by the light grey parts of the bars.

Table 1: Key performance parameters of the European XFEL accelerator and SASE 1 FEL undulator.

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Acknowledgements

The accelerator of the European XFEL and major parts of the infrastructure have been contributed by the Accelerator Construction Consortium, coordinated by DESY. The consortium consisted of Centre National de la Recherche Scientifique – Institut National de Physique Nucléaire et de Physique des Particules (CNRS–IN2P3, Orsay, France), Commissariat à l'Energie Atomique et aux Energies Alternatives – Institut de Recherche sur les lois Fondamentales de l'Univers (CEA–IRFU, Saclay, France), DESY (Hamburg, Germany), Istituto Nazionale di Fisica Nucleare – Laboratori Acceleratori e Superconduttività Applicata (INFN–LASA, Milano, Italy), National Centre for Nuclear Research (NCBJ, Świerk, Poland), Wrocław University of Technology (WUT, Wrocław, Poland), The Henryk Niewodniczański Institute for Nuclear Physics – Polish Academy of Science (IFJ–PAN, Kraków, Poland), Institute for High Energy Physics (IHEP, Protvino, Russia), D.V. Efremov Scientific Research Institute of Electrophysical Apparatus (NIIEFA, St. Petersburg, Russia), Budker Institute of Nuclear Physics – Siberian Branch of Academy of Science (BINP, Novosibirsk, Russia), Institute for Nuclear Research – Russian Academy of Science (INR, Moscow, Russia), Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT, Madrid, Spain), Universidad Politécnica de Madrid (UPM, Madrid, Spain), Stockholm University (SU, Stockholm, Sweden), Uppsala University (UU, Uppsala, Sweden), and Paul Scherrer Institute (PSI, Villigen, Switzerland).

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P.Ab., A.Ab., C.A., V.An., E.A., D.A., V.Ay., N.B., P.Ba., V.Ba., R.Ba., S.Bar., O.Be., V.Belo., L.Be., V.Bely., S.Be., M.Be., B.Be., C.Bo., M.Bö., E.Bon., M.Bon., A.Bo., R.Bö., M.Bou., J.B., F.Br., H.B., A.Brü., L.Bu., T.Bü., J.Ca., E.C., J.Cha., J.Che., A.Che., V.C., M.Chi., A.Cho., S.Ch., M.Cho., D.C., W.Ci., C.C., K.C., M.Cz., B.D'A., H.D., A. dZW., W.D., A.De., T.De., M.Doh., A.Do., N.D., P.D., F.E., A.E., J.Es., S.E., A.Fa., M.Fel., M.Fen., K.Fl., V.F., M.Fo., L.F., M.Fu., J.Fy., A.Ga., L.G., C.G., V.G.,

M.Gl., J.G_., A.Go., Z.G., N.Go., W.Grab., M.Gre., T.G., M.Gro., U.G., P.Gr., F.G., H.G., G.Gu., J.Gu., M.Ha., E.H., I.H., J.Hause., A.He., F.He., D.H., O.H., A.Hi., M.Hi., H.H., F.Ho., M.Ho., Y.H., A.Ig., A.Il., J.I., L.J., K.J., H.J., N.Jo., R.J., W.Ka., R.Ka., S.Kars., V.Ka., D.Ke., B.Ke., M.Kh., M.Ki., B.Ki., Y.Kl., R.Kl., L.Kn., S.Kö., W.Köh., A.Kon., W.Kop., A.Kos., K.Ko., D.Ko., Y.Ko., T.K., V.Ko., R.Kra., M.Kr., A.Kra., B.Kr., L.Kr., R.Kre., G.K., V.Kul., V.Kuz., M.Lac., T.La., A.La., M.Lar., D.Le., S.Le., T.Le., J.Lie., L.L., T.Li., D.Li., S.Li., B.Lo., J.L., F.Lu., K.Mac., C.Mad., C.Mag., C.Mai., I.Ma., K.Mal., E.M., B.M., F.Ma., G.Ma., T.Mar., W.Mas., M.Ma., A.Ma., U.M., J.Me., K.Me., G.Mi., P.Mi., F.Mo., C.Moh., W.Mö., M.Mom., L.M., C.Mon., M.Mor., I.Mo., P.Mo., C.Mül., J.Mül., K.Mü., V.M., O.N., N.Ne., R.Ne., R.Ne., D.N., F.O., I.O., M.Om., A.Op., A.Ot., M.Ou., C.Pa., R.P., V.Pa., C.Pe., A.Per., F.P., A.Pet., S.Pf., S.Ph., Y.P., P.P., S.Pi., E.P_., M.Po., J.Po., V.Po., S.Pr., G.P., H.P., K.P., E.Py., S.R., K.R., D.R., C.R., J.Roe., M.R., J.Rot., E.R., R.R., H.Sa., O.S., H.Sc., V.Sc., C.Schm., F.Sc., M.Schmi., M.Schmö., E.Sc., M.Scho., J.Schu., J.Se., E.Se., D.Ser., N.Sh., P.Sh., L.Sh., D.Si., C.Si., W.S., X.S., N.Sk., P.Sm., T.So., M.Sta., M.Ste., B.St., N.St., F.St., M.Stol., A.Su., R.S., C.Sy., V.Sy., J.Th., A.Th., D.Ti., F.Ton., F.Tor., I.T., D.Tr., G.T., T.Tr., G.Var., G.Vas., A.V., S.V., B.V., M.Vi., E.Vog., E.Vol., R.Wa., N.W., T.Wa., H.Wed., R.We., M.We., C.W., T.Wi., I.W., L.W., M.Win., K.Wi., P.W., T.Wo., M.Wo., G.Wr., B.Y., M.Yu., I.Z., A.Zav., D.Za., A.Zhu., V.Z., N.Z., F.Z., D.Zy. have contributed to the design, construction and commissioning of the accelerator. S.A., K.Ap., F.Ba., B.Ba., V.Bo., U.B., S.Broc., O.Br., N.C., F.D., M.Dom., X.D., W.E., J.Ei., U.E., B.F., K.Fi., I.F., W.F., T.F., G.Ge., N.Ge., P.Ge., A.Gr., J.Gr., S.G., S.Ha., M.Il., M.Iz., N.Ja., U.J., M.Ji., S.Kara., A.Koc., N.Ko., Z.K., N.Ku., D.La., Y.L., J.Liu., H.L., T.Mal., M.Me., J.Mun., A.Mü., I.P., J.Pf., M.Pl., L.Sa., D.Sa., C.Schu., S.S., M.Sik., A.Si., H.Si., A.So., E.Sy., J.Sz., K.T., J.To., S.T., A.Tr., M.Van., C.V., R.V., F.W., K.Wr., M.Ya., F.Y., P.Z. have contributed to the design, construction and commissioning of the photon system.
A.Ag., P.Al., P.Al., K.Am., S.Baa., A.Bl., M.Bl., T.Bö., P.Bo., C.Bö., E.Boy., Y.B., S.Brie., S.Brin., G.C., M.Cl., W.Cl., J.Co., J.D., T.Di., M.Dr., M.Du., H.E., C.E., K.E., M.Fa., J.Fe., S.F., A.Fr., M.Fr., O.G., L.H., R.H., A.Ha., J.Hausc., J.Havli., N.H., T.H., J.J., M.Je., D.Ka., H.Ka., K.Ka., M.Ko., W.Koo., M.Kö., O.Ko., A.Kot., O.Kre., J.K., O.Krö., K.Kr., H.Ku., D.Le., A.Le., F.Le., B.Li., W.Mac., H.M., N.Me.,

N.Mi., M.Moe., S.M., D.M., J.Mue., B.N., N.Ng., J.O., J.Pe., B.P., J.Pr., B.R., A.R., W.R., M.Sa., F.Sa., J.Scha., M.Schl., T.Sc., B.Sc., D.Sel., M.Sie., K.S., M.Stod., J.Sw., N.T., F.U., P.V., M.Vas., G.We., M.Wie., A.W., A.Zhi., A.Zol. have contributed to the facilities infrastructure, radiation protection and general safety. M.A., A.Bra., R.Br., S.Cu., W.D., W.Grae., M.Ho., M.Hü., A.Sc., T.Ts., H.Wei., R.Wi. have managed the construction of the facility. W.D. wrote the manuscript draft with input from M.Y., T.T, J. Pf., J. Gr.. The experiments were performed by K.Ap., B.Be., U.B., J.B., F.Br., W.D., M.Dom., W.F., L.F., G.Ge., N.Ge., C.G., J.Gr., M.Il., M.Iz., R.Ka., S.Kara., A.Koc., Z.K., N.Ku., D.La., Y.L., T.Li., D.Li., S.Li., T.Mal., M.Me., D.N., M.Om., I.P., L.Sa., D.Sa., E.Sc., M.Scho., S.S., M.Sik., H.Si., S.T., T.Wa., P.Z..

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Competing interests

The authors declare no competing interests.

Data availability

The data that support the plots within this paper and other findings of this study are available from the corresponding authors upon reasonable request.

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Fig. 1: Bird's-eye view of the facility showing the location of the tunnel buildings in the urban area of the city of Hamburg. The injector is on the right on the DESY campus, while the experiment hall and headquarters of the European XFEL are on the left in the federal state of Schleswig-Holstein. Note the fan of five photon beamlines entering the experiment hall.

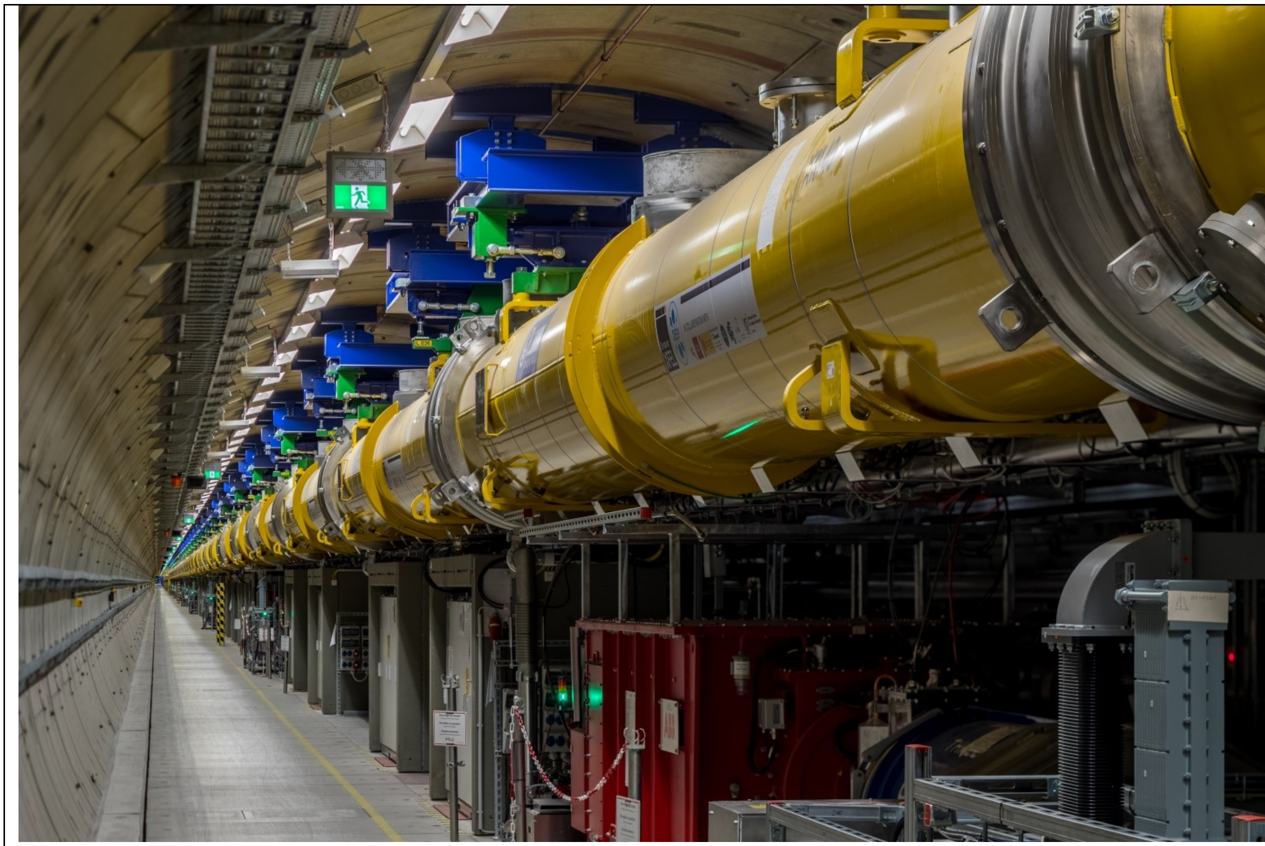

Fig. 2: View along the almost 1 km long superconducting linac section L3, which accelerates the beam after the last bunch compression stage from 2.5 GeV up to 17.5 GeV. Note that the accelerator is supported from the tunnel ceiling, while the complete infrastructure (high-power RF, electronics, and auxiliaries) is installed on the tunnel floor for easy maintenance and access.

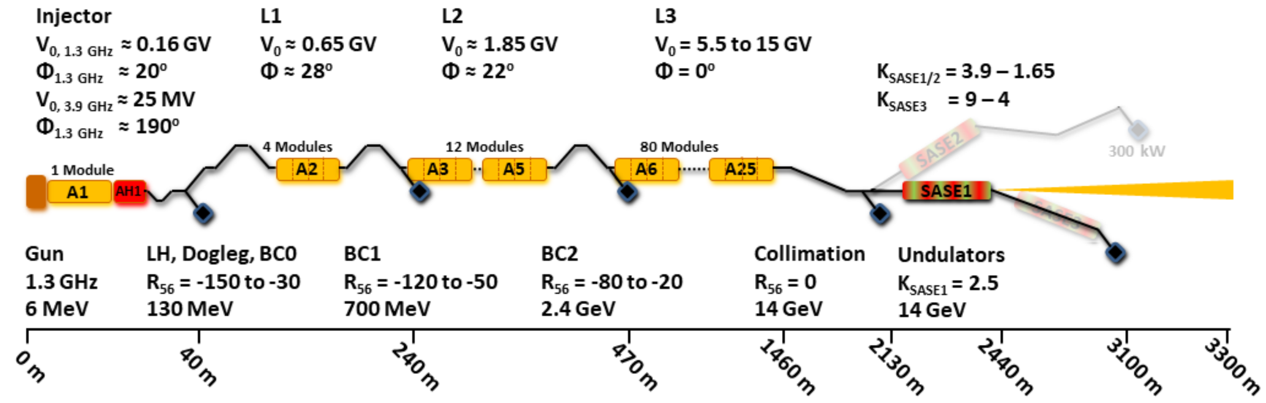

Fig. 3: Schematic layout of the European XFEL accelerator and photon beam transport as used in the first lasing and initial operation phase.

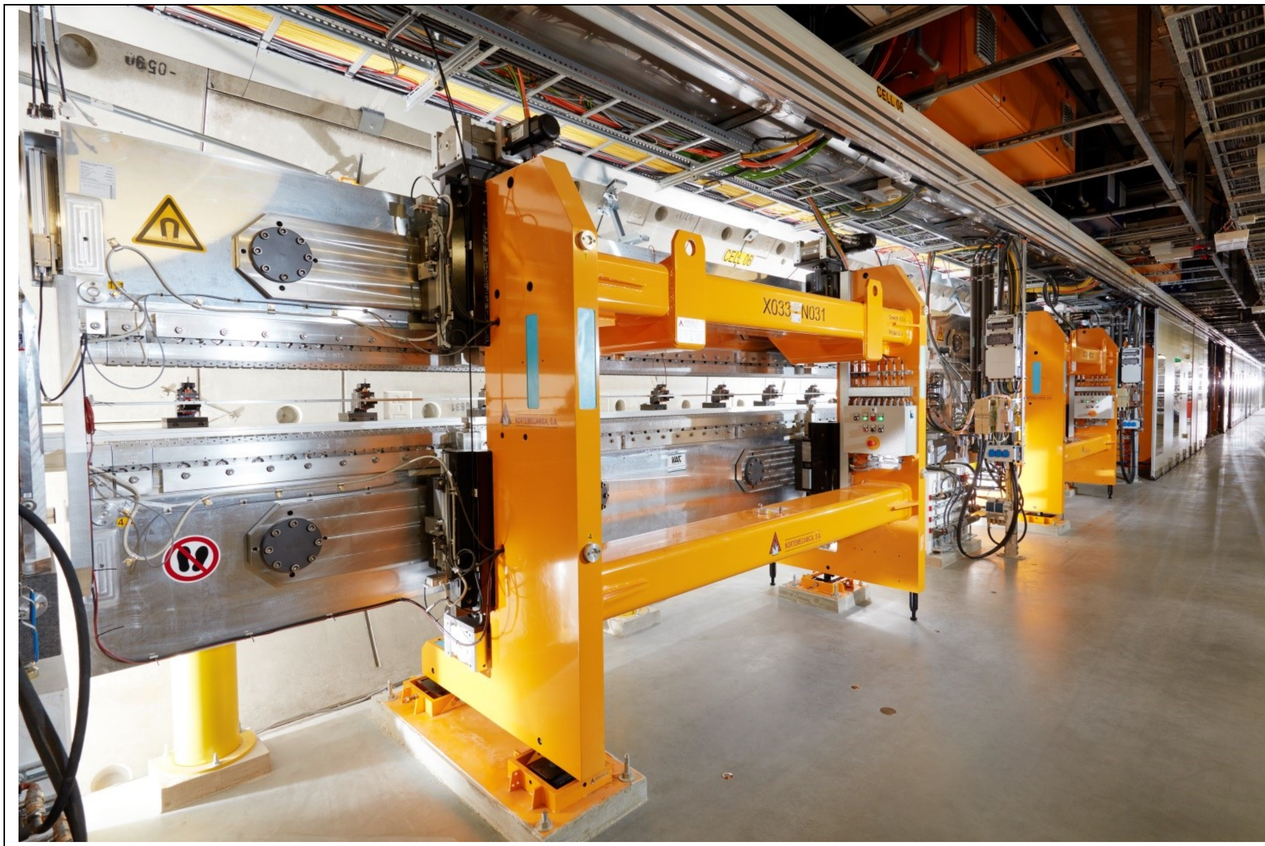

Fig. 4: View of the undulator installation in the tunnel. A 5 m long undulator segment is shown in front, while the 1.1 m intersection with the BPM, quadrupole magnet, and phase shifter is partially hidden from view on the right side of the undulator. During operation, the complete undulator is enclosed in climate housing. Panels of the removable housing can be seen to the far right.

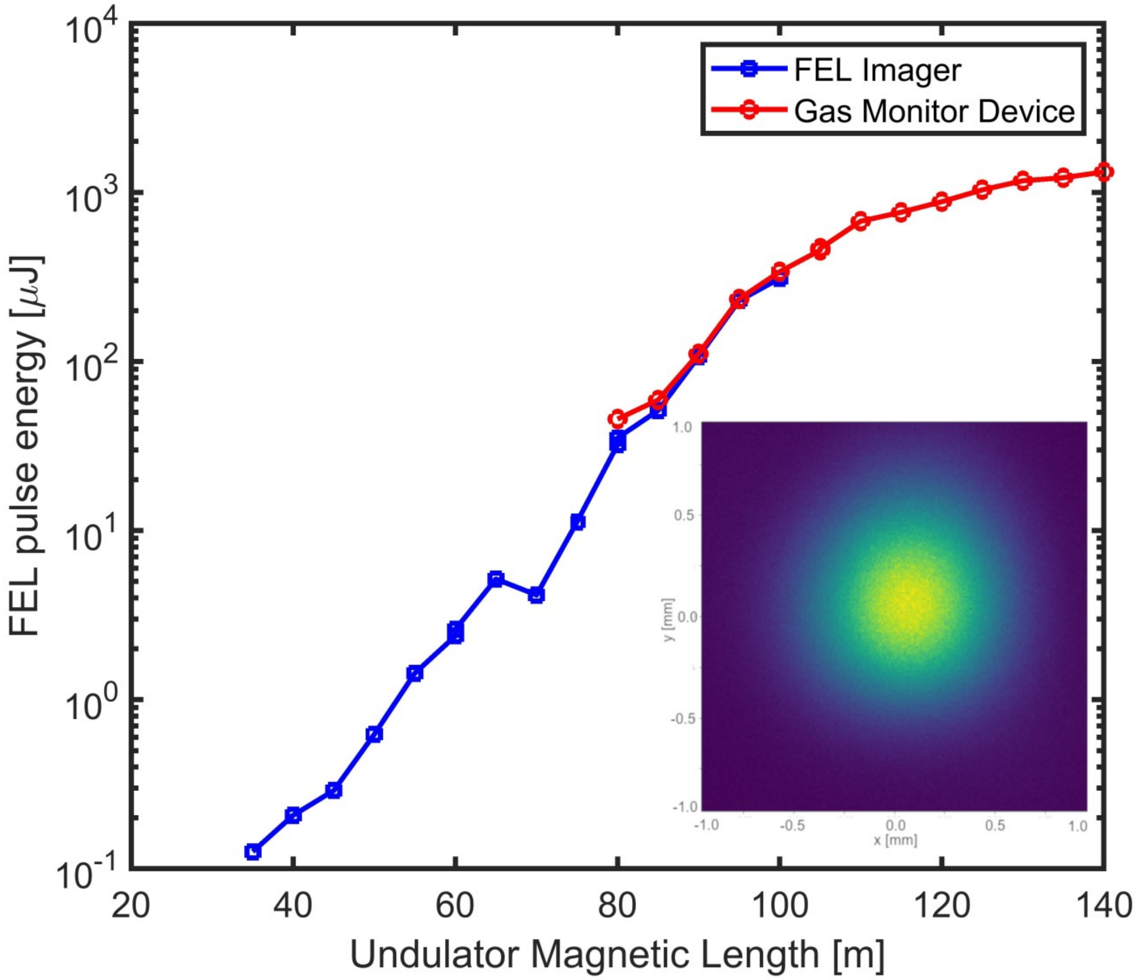

Fig. 5: The integrated FEL pulse energy as a function of the undulator magnetic length measured by the transparent X-ray gas monitor device (XGM, red) and the invasive FEL imager (blue). For the FEL imager, a summed image of ~1500 trains is used for each undulator length (the inset shows a single image for 100 m undulator length). The XGM value is averaged over all trains. The FEL imager values are normalized to the XGM value at an undulator length of 90 m.

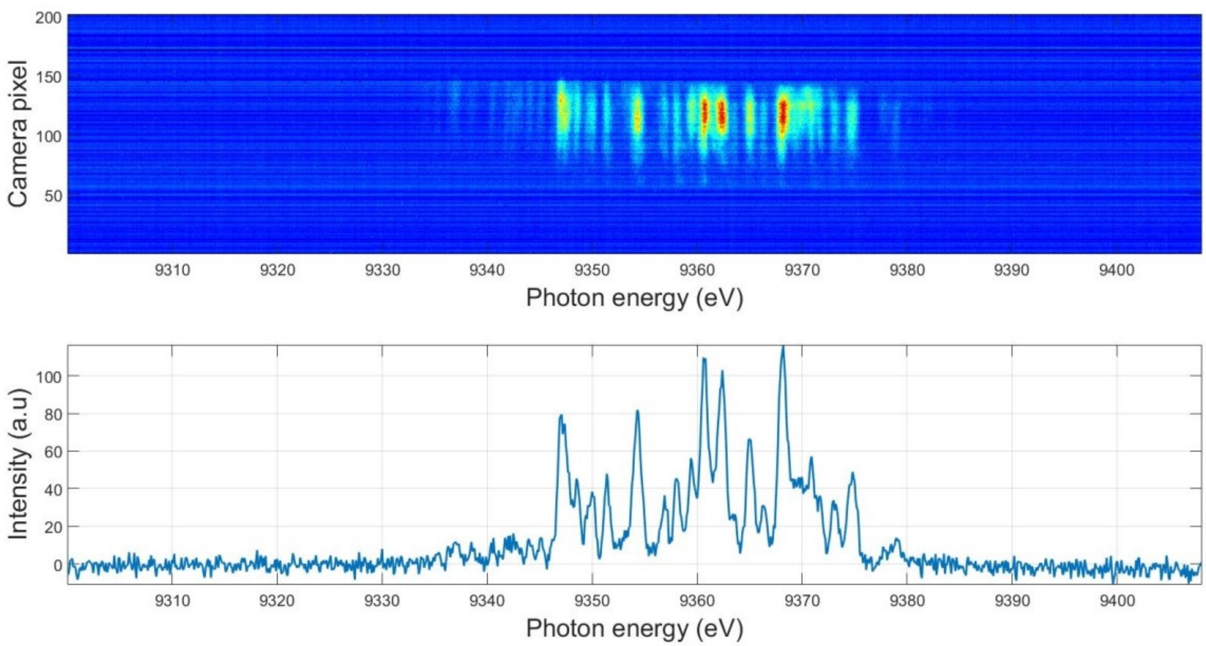

Fig. 6: The SASE spectrum measured by the HiREX single-shot spectrometer. The top figure shows the single-shot spectra collected at 9.36 keV with an electron energy of 14 GeV and 500 pC bunch charge. The bottom figure shows the line profile of the above spectrum.

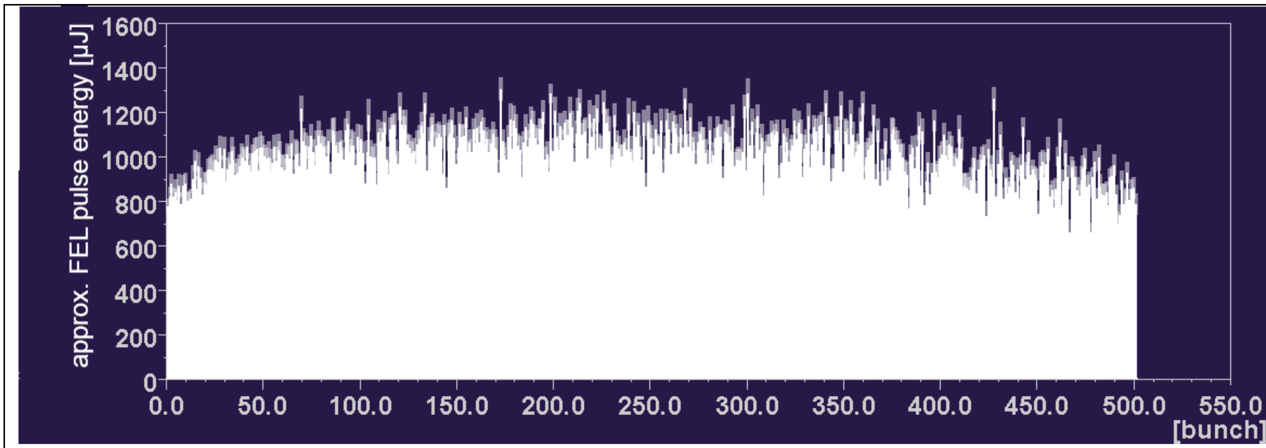

Fig. 7: SASE FEL pulse energy measured for each X-ray pulse of a train of 500 bunches. The measurement error is indicated by the light grey parts of the bars.

Parameter		Design	At first lasing and operation
Energy range	GeV	8–17.5	14
Bunch charge	pC	20–1000	250,500
RF pulse repetition rate	Hz	10	10
RF pulse length	µs	600	600
Number of bunches within RF pulse		1–2700	1-500
Peak current	kA	3–5	5
Bunch length (RMS)		3–150	20, < 50
Norm. slice emittance	mm mrad	0.4–1.0	< 0.6
Undulator active length	m	175	140
Period length , λ	mm	40	40
K parameter		3.9–1.65	2.9
Undulator average ß function	m	15–60	32

Table 1: Key performance parameters of the European XFEL accelerator and SASE 1 FEL undulator.