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THE COMMISSIONING OF THE EUROPEAN-XFEL LINAC AND ITS PERFORMANCE*

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Abstract

The main linac of the superconducting accelerator of the European XFEL presently consists of 96 accelerator modules, each housing eight 1.3 GHz TESLA-type cavities, with an average design gradient of 23.6 MV/m. The performance of each individual module has been tested after module assembly in the Accelerator Module Test Facility (AMTF) at DESY. The 2-year period of module installation to the accelerator tunnel was finished in August 2016. In order to recheck and re-establish the performance of the input power couplers, warm processing of nearly all installed modules was performed before the first cool-down during Dec 2016 / Jan 2017. Four consecutive modules are connected to one 10 MW klystron and form a so-called RF station, which is powered and controlled individually during operation. By June 2017 23 of 25 RF stations have been commissioned for beam acceleration including frequency tuning, various calibrations and LLRF adjustments. A preliminary beam energy of 14 GeV was achieved, which is sufficient for first lasing experiments. No significant performance degradation has been observed so far. The commissioning experience and the available RF performance data will be presented.

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 with a design energy of 17.5 GeV [3]. The linac operates in 10 Hz pulsed mode (1.4 ms RF pulse length) 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 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), 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. In 2010 the 800 series cavities have been ordered and the assembly of the first prototype module took place at CEA/IRFU. Series cavity delivery started in late 2012, ramping up to full production rate in Oct. 2013 and continued until end of 2015 [4, 5]. The assembly of the 102 series modules at CEA/IRFU [6] and testing at AMTF [7, 8] began in 2013 and finished in 2016. The commissioning of the linear accelerator started end of 2016.

SRF FACILITY LAYOUT

The main linac 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 seven-story 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 with a Cs2Te-cathode [9, 10, 11]. The photo-injector is followed by a standard superconducting 1.3 GHz accelerator module and a 3rd-harmonic linearizer, consisting of one 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.

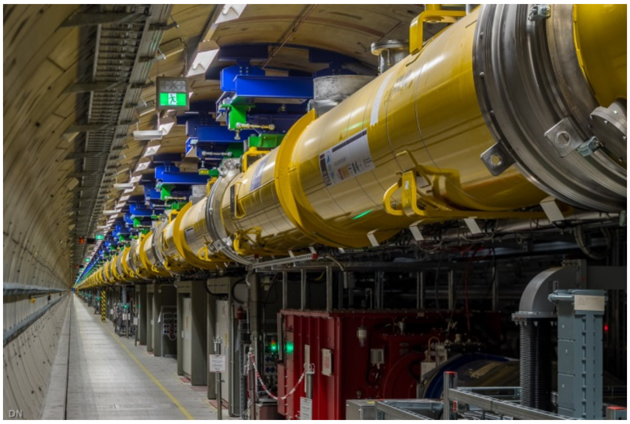

Figure 1: View into the linac tunnel with the accelerator modules suspended from the ceiling and the RF infrastructure placed below on the floor.

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The superconducting linear accelerator presently consists of 96 TESLA type accelerator modules, each housing eight 1.3 GHz TESLA-type cavities. Always 4 modules are fed by one 10 MW multi-beam klystron (one RF station). The accelerator modules are suspended from the ceiling (see Fig. 1), 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. Downstream to about 50 m behind the last cryomodule, the complete beam vacuum system is cleaned "particle free" to the cleanliness standards applied for high performance SRF cavities.

In total 103 accelerator modules have been assembled at CEA/IRFU Saclay of which 96 modules were assembled in 103 working weeks into the main tunnel and one module to the injector. Of the remaining six modules, one is spare (XM100) and four require rework due to degraded cavity performance or leaks (XM8, XM46, XM50, XM99) [12, 13]. Finally, XM-3 is equipped with non-PED certified cavities and used for extensive cw-tests.

A schematic overview of the European XFEL accelerator is shown in Fig. 2. The two RF stations A24 and A25 require final installation work and are not yet commissioned.

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 superconducting accelerator of the injector was cooled down in December 2015 and first electrons were accelerated to 130 MeV on Dec. 18th [14]. Also at that early stage the 3rd-harmonic lineariser was commissioned and operated at the design gradient throughout the complete run [15, 16]. The injector commissioning was ended in July 2016 to connect the cryogenic distribution boxes of the main accelerator to the cryo-infrastructure. During this commissioning most of the design parameters of the injector could be reached or even exceeded.

Standard operation voltages during the commissioning of the main linac in spring 2017 were about 150 MV for the 1.3 GHz module and about 20 MV for the 3rd-harmonic module with both cryomodules operated well below the individual cavity limits.

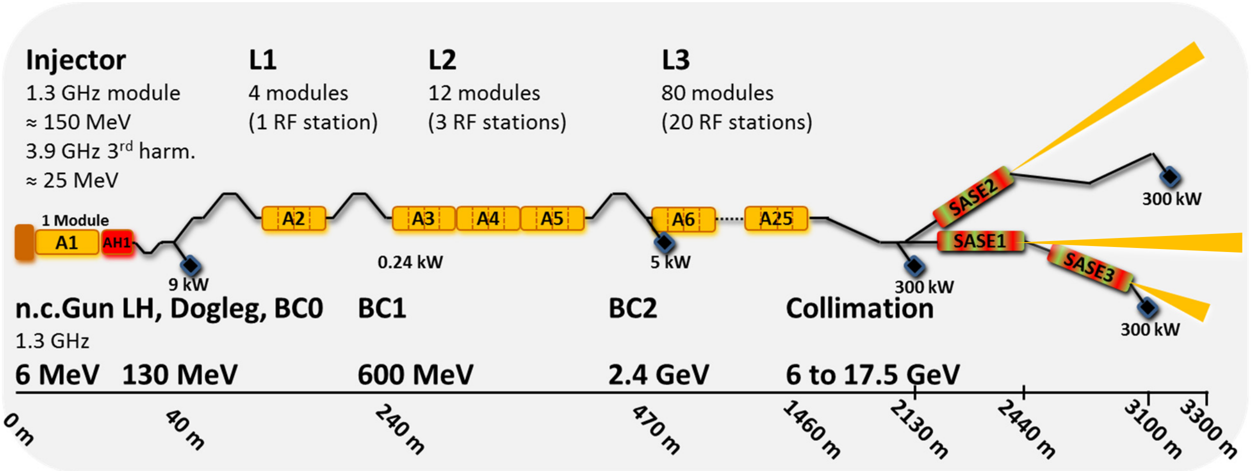

Figure 2: Schematic overview of the European XFEL accelerator. Single RF stations are named A*nn* and feed either one module (A1) or 4 modules (A2-A25). The maximum allowed beam power of the three commissioning dumps after the injector and the 2nd and 3rd bunch compressor (BC1 and BC2) as well as of the main dumps after the linac and each beam distribution line is given.

Cryogenic System

The European XFEL cryogenic system consists of two overhauled strings of the HERA cryo-plant, a new distribution box and transition line to the European 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, 4 kW in the 5-8 K circuit and 26 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 [17]. Start-up of the cold compressors enabled the handover of the accelerator at 2 K beginning of January. Problems with the lifetime of the cold compressor engines could be identified and an improved design is under implementation [18]. 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% [18]. Preliminary measurements show no unexpected enhanced static losses of the system [17].

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Electronics and Control System

The frontend 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 [19, 20]. 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. Graphical user interfaces to control each subsystem are available and can easily be re-configured using the jDDD toolkit [21].

Linac Commissioning

The commissioning of the XFEL accelerator began mid of January 2017 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 commissioning.

LLRF commissioning was given highest priority. At this time 23 of the 25 RF stations are available. For each of the RF stations a sequence of steps had to be performed [22, 23]. 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 initial 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 [24].

Already at the end of April a beam energy of 12 GeV at the end of the linac was achieved. On May 2nd the first lasing was observed and in June the first beam with a wave length of 0.15 nm could be transported to the experimental area followed by the first diffraction pattern.

The phase and amplitude stability was measured inner loop to be better than 0.01° and 0.01%.

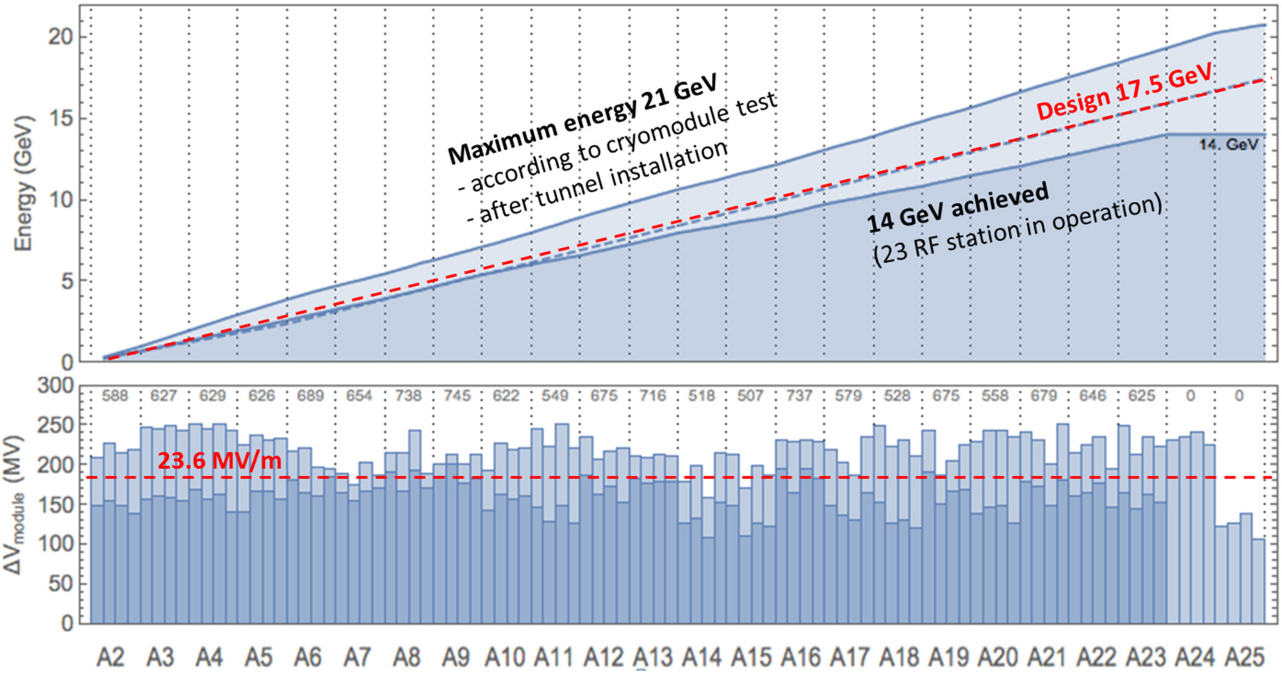

Figure 3: Comparison of expected (light blue) and achieved (dark blue) energy (top) and accelerating voltage (bottom) for the RF stations A2 to A25 in the main linac. A24 and A25 require final installation work and are not under commissioning.

Accelerator Module Performance

After cavity production all cavities got an acceptance test in the AMTF [5] at DESY before they were sent for string and module assembly to CEA/IRFU. Testing of the accelerator modules with respect to their RF performance, cryogenic losses, leak tightness and mechanical and electrical conformity took place in the AMTF. A major bottleneck in fulfilling the initially projected rate of one module assembly, testing and installation to the linac tunnel per week was the availability of RF input power couplers. This was compensated by additional efforts at CEA/IRFU with respect to an accelerated assembly rate. In addition, the experiences gained with module testing allowed to shorten the test duration after about 40 modules [25]. Towards the end of module production the major non-conformity was overheating of the 70K coupler window, which in several cases required an exchange of the so-called warm coupler part [24, 26]. If necessary, modules were re-tested after repair [12]. The variation of individual cavity gradient performance after string assembly required an individual tailoring of the waveguide system in order to get the maximum accelerating voltage for the given RF set-up with one klystron feeding 4 modules (32 cavities). Within the technical limits of the waveguide distribution it was more efficient to short 5 low-performing cavities. For tunnel installation the modules were sorted based on their test performance.

The average usable gradient in the cryomodule test is (27.5±4.8) MV/m compared to (28.3±3.5) MV/m in the vertical test respecting the available RF power, and is well above the required average design gradient of 23.6 MV/m. An overview of the module RF performance in the AMTF test is given in [7, 8].

The maximum energy in the linac is given by

- The cryomodule performance in the AMTF test.
- The reduction of available gradient by the boundary conditions of the waveguide distribution for each individual module and the tunnel installation [7].
- The configuration of the bunch compressors, specifically the required bunch compressor energy at the exit of BC2 (2.4 GeV).
- The number of operational RF stations: At present 23 RF stations are initially commissioned and two stations require final installation work.

Assuming all 25 RF stations in operation the above described technical boundary conditions lead to a maximum energy of 19.5 GeV. Neglecting the bunch compressor working point of BC2 results in a maximum energy of 21 GeV. At present with 23 RF stations available 14 GeV has been achieved (Fig. 3) after initial commissioning. No indication for significant degradation of individual cavities compared to their AMTF test performance has yet been observed. For final commissioning the waveguide distribution, RF and energy calibrations and status of RF conditioning for each RF stations are under further careful investigation with first positive results.

A preliminary analysis of the dynamic cryo losses during operation of 23 RF stations at 12-14 GeV resulted in an average Q-value above 10^{10}.

OUTLOOK

The European XFEL accelerator has been put into initial operation reaching the commissioning targets. The accelerator will be further developed towards higher energies and beam power. First user experiments are scheduled for September 2017. 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.

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