# STATUS OF THE EUROPEAN XFEL – CONSTRUCTING THE 17.5 GeV SUPERCONDUCTING LINEAR ACCELERATOR

W. Decking, DESY, Hamburg, Germany
for the European XFEL Accelerator Construction Consortium*

*Abstract*

The European XFEL is presently under construction in Hamburg, Germany. It consists of a 1.2 km long superconducting linac serving an about 3 km long electron beam transport system [1]. Three undulator systems of up to 200 m length each produce hard and soft x-rays via the self-amplified spontaneous emission (SASE) process. We will present the status of the civil construction and the accelerator components. The production of the 100 superconducting accelerator modules is distributed between industries and a collaboration of accelerator laboratories. We describe the carefully orchestrated production sequence, quality assurance measures and risk mitigation mechanisms. The last module is scheduled to be installed in the accelerator in spring 2015 and commissioning with beam will start in summer of that year.

## OVERVIEW

The European XFEL is being constructed as an European Research Infrastructure under the participation of 12 European countries. The construction of the electron accelerator is entrusted to a consortium of 16 laboratories led by DESY, Hamburg. The laboratories contribute to the accelerator 'in-kind', i.e. by delivering sub-systems and parts under their own responsibility.

The facility will provide hard and soft X-rays for a wide range of scientific applications. In its initial stage it will host three independent photon beam lines serving two experiments each. Final extension will show three experiments for each of the five independent photon beam lines.

The European XFEL employs superconducting accelerator technology, leading to unique features compared to other X-ray FELs being constructed or in operation worldwide. It is capable of accelerating up to 27000 bunches per second, distributed into 10 pulses of 600 μs length. Bunches can be injected into two separate electron beam lines hosting two resp. up to three undulators in a row. Flexible bunch patterns and plans to provide individual bunch properties will make the European XFEL a true multi-user facility.

Progress in the electron gun development for the European XFEL and the success of LCLS led to a redefinition of the expected accelerator performance. The final energy of 17.5 GeV, together with the long undulators and the anticipated low emittance beams out of a photo-cathode gun will allow reaching photon wavelength as short as 0.5 nm [2].

The installed linac and its infrastructure bear the possibility to be converted into a CW (or quasi-CW) accelerator in the future with the potential to reach up to 6 GeV final energy (for an update on the R&D towards this option see [3]).

Table 1 gives an overview of the main parameters of the facility.

Table 1: European XFEL Parameters

| Quantity | Value |
|---|---|
| maximum electron energy | 17.5 GeV |
| macro pulse repetition rate | 10 Hz |
| RF pulse length (flat top) | 600 μs |
| bunch repetition frequency within pulse | 4.5 MHz |
| bunch charge | 0.02 – 1 nC |
| electron bunch length after compression (FWHM) | 2 – 180 fs |
| beam power | 500 kW |
| # of modules containing eight 9-cell superconducting 1.3 GHz cavities | 101 |
| accelerating gradient for 17.5 GeV | 23.6 MV/m |
| # of 10 MW multi-beam klystrons | 27 |
| average klystron power for 0.03 mA beam current at 17.5 GeV | 5.2 MW |
| photon wavelength | 0.05 – 4 nm |

A normal-conducting photo-cathode RF gun produces high brightness electron beams. The injector building allows the later installation of a second, completely independent injector. The main linear accelerator is sectioned into three units with 4, 12 and 84 modules each, intercepted by normal conducting bunch compressor and diagnostic sections. A collimation and beam distribution section follows the linac, where the beam can be fed into the two separate undulator beam-lines and/or a commissioning and pulse-picker dump. Each beam-line is terminated by a solid state beam dump capable of accepting up to 300 kW of continuous beam power. The SASE photon beam is delivered through up to 800 m long photon beam lines to the experimental hall. See Fig. 1 for a bird's eye view of the facility.

* BINP Novosibirsk, CEA Saclay, CIEMAT Madrid, CNRS Orsay, DESY Hamburg&Zeuthen, IFJ-PAN Krakow, IHEP Protvino, INFN Milano, INR Troitsk, NCBJ Swierk, NIIEFA St. Petersburg, PSI Villigen, SU Stockholm, UPM Madrid, UU Uppsala, WUT Wroclaw




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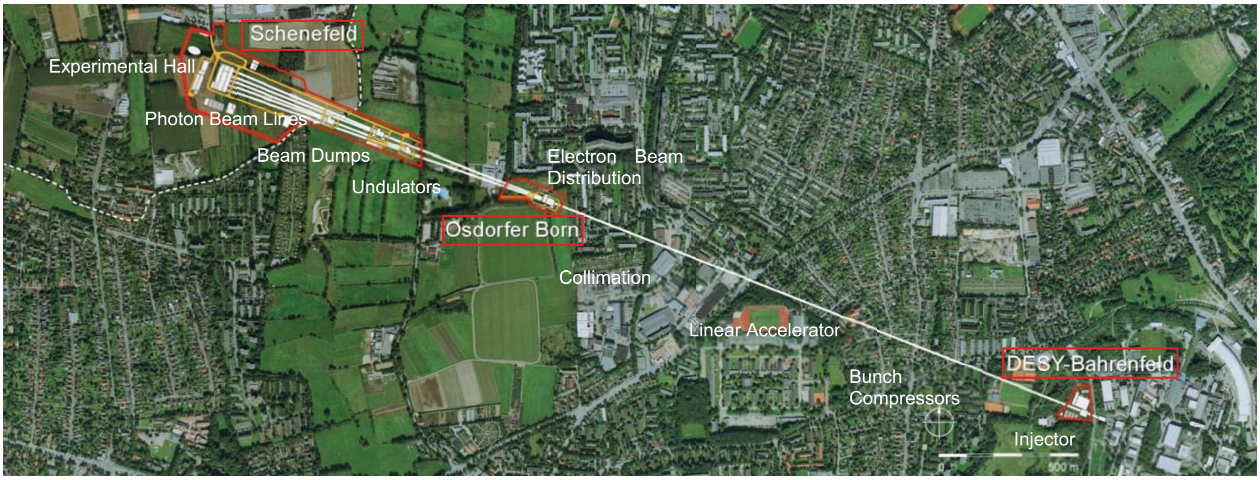


Figure 1: Bird eye's view of the European XFEL site showing the location of the three surface areas and the tunnel routing below the cities of Hamburg and Schenefeld.

## STATUS

### *Civil Construction*

The European XFEL requires a large amount of civil construction at three construction sites: on the DESY campus the injector building, modulator hall and accelerator module test facility (AMTF), the large experimental hall, tunnel separation shafts, dump shafts, office buildings and infrastructure buildings on the future XFEL experimental campus at Schenefeld 3.3 km to the west of DESY and a tunnel separation shaft and surface infrastructure buildings in between (see Fig. 1). About 5.8 km of underground tunnel connect these construction sites and fan out on the Schenefeld campus. They will host the accelerator and up to 5 independent photon beam lines and were constructed with the help of two tunnel boring machines. Work started in July 2010 and finished in June 2012, well within schedule (see Fig. 2).

Figure 2: View of the completed accelerator tunnel.

About 150000 $m^3$ of underground buildings had to be excavated and built. Most of the tunnel connection underground halls are finished, while the experimental hall is projected to be delivered in 2013.

Finally 12000 $m^2$ of surface buildings have to be erected. Most of the surface buildings on the DESY campus are about ready with the AMTF already close to start operation, the surface buildings on the other sites are only just being started. Their completion is of utmost importance for the machine installation, as they host the access devices like cranes and elevators and also mayor parts of the infrastructure.

### *Infrastructure Installation*

With the hand-over of the main accelerator tunnel the installation of the technical infrastructure into the accelerator tunnel has begun. It will last until 2013 before first accelerator components can be delivered into the tunnel. In parallel infrastructure installation takes place in the other tunnels, shafts and buildings as they become available [4]. Planning of the infrastructure for the accelerator and the future experimental campus is a major task for DESY.

### *Accelerator Components*

Apart from the superconducting accelerator about 3 km of so-called 'warm' beam lines have to be installed.

The photo-cathode gun will be of the same type as already in operation at the FLASH facility, DESY Hamburg, and the Photo-Injector Test Stand Zeuthen (PITZ), DESY Zeuthen. The gun body foreseen for the European XFEL is manufactured and will be conditioned and characterized at PITZ in the coming 9 months. The photo-cathode laser will be supplied by the Max Born Institute under the responsibility of DESY. It uses Yb:Yag lasing material and a pulse stacking system to provide a > 20 ps flat top with a steep rise and fall time.

The warm electron beam vacuum system is constructed by BINP and DESY. Up to a distance of 30 meters from the superconducting accelerator the vacuum system has to be particle free to avoid contamination of the cold modules in case of a vacuum leak in the warm vacuum. The undulator vacuum chambers, made of aluminium with stringent specifications on the surface roughness and oxide layer to minimize resistive wall wake fields, pose an additional challenge.

Normal conducting magnets are produced by BINP and Efremov Institute. A total of more than 700 electro-magnets have to be delivered. The more than 120 undulator quadrupoles used for the focussing lattice in the undulator section are already on site, while the first batch of magnets that will be installed in the injector is due in autumn this year.

Beam instrumentation consisting of beam position and charge monitors, transverse beam profile monitors and various devices to measure longitudinal bunch properties are provided by DESY, PSI and INR. Most diagnostic devices have been developed and tested at FLASH and are now in the final engineering phase or already in series production.

A synchronisation system allows the measurement of beam arrival at certain stations up to 10 fs accuracy. Lasers and other devices can be locked to this system to allow synchronised pump-probe experiments [5].

The three undulator systems use moveable gap undulators of 5 m length and a period length of 40 resp. 68 mm. The contract for 91 undulators is awarded and first prototypes are on site for establishment of the fine tuning procedures.

## SUPERCONDUCTING ACCELERATOR

### *Cavity Fabrication*

The performance goal for the 800 9-cell cavities is an accelerating gradient of 23.6 MV/m at $Q_0=1\times10^{10}$.

The cavities are manufactured in industry according to the procedure previously developed at DESY (build to print). The performance is not guaranteed by the producers, in case of low performance the cavities will be re-treated at DESY. Nb sheets and parts are supplied to the producers via DESY.

The Nb sheets and tubes are produced by four different companies which have been pre-qualified for production of the required high purity sheets. All parts are individually quality controlled at DESY through an eddy current scan and tactile 3d dimension measurements before they are delivered to the cavity manufacturers.

Production of the cavities has been contracted to two companies. Both companies have erected the necessary infrastructure for the mechanical fabrication and the proper surface treatment of the cavities. After deep drawing the half cells are e-beam welded into dump bells and finally into 9-cell cavities. RF measurements and quality inspections are performed at each production step. All documentation is stored in the XFEL project EDM system by the contracting companies. The companies have also access to selected relevant information.

The surface treatment consists of an approx. 100 µm electro-polishing, ethanol rinsing, outside chemical polishing and high temperature annealing prior to cavity tuning. The cavity tuning is performed at the companies with special equipment that was developed and manufactured at DESY. After tuning the final surface treatment is either performed with another electro-polishing step or a 10 µm chemical polishing prior to the welding into the Titanium Helium vessel. Finally the cavities are dressed with auxiliary parts and higher-order mode couplers and shipped to DESY for acceptance test.

The complete procedure and infrastructure at the companies is qualified with reference cavities and pre-series cavities. First measurements of the reference cavities (production at companies and surface treatment and RF test at DESY) show performance above specification [6]. The surface treatment is established at the companies in a step-wise procedure, with the RF performance being tested after each treatment step.

Each of the 800 cavities is acceptance tested with a CW power test in a vertical cryostat. The tests are performed in a dedicated section of the AMTF hall. One vertical cryostat is already delivered to AMTF, while the 2nd is expected in November 2012. The infrastructure for vertical cavity testing is supposed to be fully operational by end of this year.

After reception and initial inspection the cavities are installed four each into an insert that allows parallel cool down and testing. The complete procedure of assembly, cool down, testing, warm up and disassembly will take about one week. The testing is performed by a team of specialist from IFJ Krakow. Presently the training and development of all steps is performed at the existing DESY infrastructure.

Accepted cavities will then be shipped to CEA Saclay for string assembly. A limited number of non-conforming cavities can be re-treated at the DESY infrastructure.

### *Module Assembly*

The module assembly integrates all individual parts of a super-conducting module [7]:

- The power couplers are procured and warm conditioned by LAL Orsay. The copper plating of coupler parts turned out to be more challenging than anticipated and the involved parties work hard on the solution of the remaining problems.
- The cavity tuners are delivered by DESY.
- The cold vacuum pieces like bellows and intersections are made available by BINP Novosibirsk and DESY.
- The cold quadrupole package, consisting of a super-conducting quadrupole/steerer package delivered by CIEMAT Madrid to DESY, where the magnets are tested and equipped with a vacuum insert for rf-shielding.
- Beam position monitors both from DESY (button type) and CEA Saclay (re-entrant cavity type). The BPMs are connected to the quadrupole in the clean room at DESY and the complete unit is integrated into the cavity string.
- Cold masses from INFN Milano and DESY.

Module assembly starts with the assembly of the cold coupler parts to the individual cavities in an ISO4 clean room. Eight cavities are then connected together with the quadrupole package into one cavity string, again under ISO4 clean room conditions. The cavities in the string are then equipped with tuners and magnetic shielding. The 2K He pipe is welded together and the complete string is connected to the He return pipe (cold mass), see Fig. 3. The cold mass is responsible for the mechanical rigidity of the system. All components are carefully aligned to each other and insulation shields and superinsulation are installed. Finally the cavity string/cold mass assembly is inserted into the cryostat. The warm parts of the couplers are installed and the coupler vacuum system is connected. The string is aligned within the cryostat and the complete assembly is prepared for transportation by assembly of end-caps, nitrogen filling of the cavities and assembly of surveillance instrumentation.

The string and module assembly is performed at CEA Saclay. Dedicated infra-structure has been set up during the past years, consisting of clean rooms, assembly halls, offices and ware houses [8]. Assembly of one module per week is foreseen. All critical parts of the infrastructure are laid out redundant to allow for maintenance, correction of non-conforming assembly steps or eventually a higher assembly rate.

Figure 3: Assembly of the cold mass at CEA Saclay.

Commissioning of the infrastructure and training of CEA staff has been performed since 2010 through the assembly and disassembly of XFEL prototype modules. The final assembly of 103 modules (3 pre-series and 100 series modules) is done by an industrial operator under the supervision of CEA staff. The respective company has been selected and the contract signed, training will start in autumn this year on the pre-series modules.

An assembly rate of one module/week requires careful planning of all logistics. On one hand a sufficient supply of sub-components has to be available on site, while on the other hand storage space is limited and the production of sub-components is just ramped up in time to match the assembly schedule. At least weekly video conference meetings of all involved parties are necessary despite the careful planning involving modern project planning tools.

After assembly the modules are transported by truck to DESY. A special shock absorbing frame is used to avoid misalignment and damage to the module. Shock-meters are in operation during the transport to record any unusual acceleration. The road transport has been tested with an assembled and tested module and no performance degradation has been observed.

Each of the 103 modules is tested at DESY at the AMTF. Three individual test stands (see Fig. 4) allow a through put of 1 tested module per week. The complete procedure of installation on the test bench, cool-down, testing, warm-up and disassembly is estimated to take about 2 weeks. The task is performed by the same specialist team responsible for the testing of the modules.

Figure 4: View of the module test stand in the AMTF.

Conforming modules can be stored partially on the DESY site for later installation. A small percentage of non-conforming modules could be disassembled and repaired in the DESY infrastructure.

## *RF System*

An RF system unit consists of a 10 MW multi-beam klystron, pulse transformer, modulator and the wave-guide distribution to the individual input couplers. Contracts for all components are placed with industry.

The modulators will be placed outside of the tunnel in a dedicated hall on the DESY site. The pulse is fed into the tunnel with up to 2 km long pulse cables. These cables will be installed in the lower section of the tunnel below the floor slabs that form the transport way in the tunnel. Most of the cables are delivered and their installation into the tunnel will start this year before the floor slabs will be put finally into place.

Except for the injector and the photocathode gun one klystron feeds 4 modules (32 cavities in total). The pulse transformer and klystron are placed in the tunnel below the modules. This requires the klystron to be oriented horizontally. Prototypes of the multi-beam klystrons are in operation at the FLASH facility and show good performance [9].

The LLRF system for regulation of the RF has been developed at FLASH during the past years. In its final version it is based on the MicroTCA industrial standard. In-loop and outer-loop performance measurements show an RMS amplitude and phase regulation of $\Delta A/A = 5 \times 10^{-5}$ and $\Delta\Phi = 0.009^\circ$, resulting in an expected beam energy stability lower than 0.005% [10], [11].

Development of this system has greatly benefited from activities in the framework of the ILC R&D [12].

### *Accelerator Installation*

The complete accelerator will be installed into the approximately 5.4 m diameter underground tunnel. The modules are suspended from the ceiling. This allows installing rf components and electronics easily accessible below the modules.

Module installation takes place in batches of 12 modules. These modules form one cryo-string. Each string is connected by string connection boxes. Some pre-sorting of modules is possible, with best performing module preferably at the beginning of the linac. Within a cryo-string, four modules with similar performance will be fed by one klystron.

Cooling is supplied by the existing cryo-plant that was previously used for the HERA accelerator. This plant is being refurbished to cope with the next 20 years of operation and the required 2K Helium production. Cryogenic components like transfer lines, valve boxes, connection boxes and test-cryostats are developed by BINP Novosibirsk, DESY, IHEP Protvino and WUT Wroclaw.

## SUMMARY

Construction of the European XFEL is well under way with the goal of first beam in the accelerator by mid of 2015. Most of the underground civil construction is finished and the surface buildings are on schedule. Infrastructure installation has started and the procurement of accelerator components is well under way. One of the biggest challenges is the timely production of 101 super conducting accelerator modules. The production sequence has been set up and full rate series production is expected in one year.

Commissioning of the European XFEL starts with the injector in mid-2014. This includes the RF gun, one 1.3 GHz module, a third harmonic system [13], the laser heater and a section that allows bunch slice diagnostics. During the one year commissioning of the injector the remaining linac can be installed in parallel. Cool down of the main linac can only start when the complete linear accelerator is installed in mid-2015. First lasing can be expected by end of 2015.

## REFERENCES

[1] M. Altarelli et al., "The European X-ray Free Electron Laser Technical Design Report", Hamburg, July 2007, DESY 2006-097.
[2] E.A. Schneidmiller, M.V. Yurkov., "Photon beam properties at the European XFEL", Hamburg, September 2011, DESY 2011-152.
[3] J. Sekutowicz, "Second CW and LP Operation Test of XFEL Prototype Cryomodule", TUPB019, these proceedings.
[4] M. Huening, "Warm Beamlines and Infrastructure in the European XFEL", TUPB015, these proceedings.
[5] H. Schlarb, "Synchronization of Accelerator Sub-systems with Ultimate Precision", TU3A01, these proceedings.
[6] A. Sulimov, "First RF Measurement Results for the European XFEL SC Cavity Production", MOPB012, these proceedings.
[7] E. Vogel, "Integration of the European XFEL Accelerating Modules", MOPB017, these proceedings.
[8] C. Madec, "Status of E-XFEL String and Cryomodule Assembly at CEA-Saclay", THPLB09, these proceedings.
[9] V. Vogel, "Results of Testing of Multi-beam Klystrons for the European XFEL", TUPLB04, these proceedings.
[10] C. Schmidt, "Precision Regulation of RF Fields with MIMO Controllers and Cavity-based Notch Filters", THPB086, these proceedings.
[11] J. Branlard et al., "The European XFEL LLRF System", IPAC'12, New Orleans, May 2012, MOOAC01, p. 55 (2012); http://www.JACoW.org
[12] J. Branlard, "LLRF Automation for the 9mA ILC Tests at FLASH", THPB085, these proceedings.
[13] E. Vogel, "Status of the European XFEL 3.9 GHz system", TUPB020, these proceedings.




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