The vacuum system of the European X-ray free electron laser XFEL

K Zapfe, M Böhner, O Hensler, D Hoppe, N Mildner, B Nagorny, K Rehlich, H Remde, A Wagner, T Wohlenberg, J Wojtkiewicz
Deutsches Elektronen Synchrotron DESY, Notkestrasse 85, D-22607 Hamburg
Email: kirsten.zapfe@desy.de

Abstract. The European X-Ray Free Electron Laser XFEL, a new international research facility, will be built at DESY/Hamburg. The XFEL will generate extremely brilliant and ultra short pulses of spatially coherent X-rays with tuneable wavelengths down to 0.1 nm, and exploit them for revolutionary scientific experiments at various disciplines. The basic process adopted to produce the X-ray pulses is SASE (Self-Amplified Spontaneous Emission). Therefore electron bunches are produced in a high-brightness gun, brought to high energy of about 20 GeV through a superconducting linear accelerator, and transported to up to 250 m long undulators, where the X-rays are generated. The beam vacuum system of the accelerator contains sections operated at room temperature as well as at 2 K in the areas of the superconducting accelerating structures, thus requiring an insulating vacuum system. In addition to standard UHV requirements, the vacuum system for this facility needs to preserve the cleanliness of the superconducting cavity surfaces. Therefore the preparation of all vacuum components for the 1.6 km long main linac includes cleaning of the components in a clean room to remove particles, installation into the accelerator in local clean rooms, and special procedures for pump down and venting. Further challenges are the undulator vacuum chambers filling more than 700 m, where a high surface quality with respect to surface roughness and thickness of oxide layers is mandatory to reduce wake field effects, and the vacuum systems for the various beam dumps, where exit windows acting as vacuum barriers of sufficient reliability need to be developed. In addition, a large amount of about 1.7 km of transport beam lines is required. The layout of the various vacuum sections as well as experience with prototype components will be described.

1. Introduction
The European X-Ray Free Electron Laser XFEL [1] is a 4th generation synchrotron radiation facility to be built near DESY in Hamburg/Germany. The purpose of this new international scientific infrastructure is to generate extremely brilliant and ultra short pulses of spatially coherent X-rays in a wavelength regime from 0.1 nm to 5 nm, and to exploit them for exciting and benchmarking scientific experiments at various disciplines spanning e.g. physics, chemistry, material science and biology. The peak brilliance will be more than 100 million times higher than at present day 3rd synchrotron radiation sources.

1 Correspondence to be addressed to kirsten.zapfe@desy.de

© 2008 IOP Publishing Ltd
The basic process adopted to generate the intense X-ray pulses is SASE, the Self-Amplified Spontaneous Emission. Therefore electron bunches are produced in a high-brightness gun and accelerated to high energy of about 20 GeV by a superconducting linear accelerator using the TESLA technology. Thereafter they are transported to up to 250 m long undulators, where the X-rays are generated. The European facility should stand apart from XFELs planned for the US [2] and Japan [3] because of its much higher pulse rate and superior pulse quality.

The European XFEL will be an international multi-user facility, with 75% of the funding for the initial construction phase provided by Germany and 25% from other partner countries. The proposal of the XFEL in 2002 [1] and principal approval by the German government as European project in 2003 was followed by an intensive phase to finalize the overall layout and technical design, resulting in a technical design report [4], to detail the planning for the new site near DESY, to industrialize major technical components, and to prepare the organizational structure of the project. Just recently the official go ahead was given to start the construction. The first X-ray beam is scheduled for 2013, and first users will gain access to the facility by the following year. However, before the accelerator is put into operation, a wide range of technical challenges must be overcome – including the development of strategies for delivering and maintaining the appropriate vacuum conditions.

A schematic sketch of the facility is shown in figure 1. In the injector, electron bunches are extracted from a solid cathode by a laser beam, accelerated by an RF gun and directed towards the linear accelerator. Consisting of a 1.6 km long sequence of superconducting accelerating structures, magnets and diagnostic equipment, the electrons are accelerated to energies of up to 20 GeV. An energy of 17.5 GeV is foreseen for the standard mode of operation of the XFEL facility at 0.1 nm FEL wavelength. Along the accelerator, two stages of bunch compression are located to produce the short and very dense electron bunches, which are required to achieve saturation in the SASE process. At the end of the linear accelerator follows a beam transport section with collimation and diagnostics systems, after which the individual electron bunches are fed into one or the other of two electron beam lines with the undulators by a beam distribution system. The linac and beam transport line are housed in a 2.1 km long underground tunnel. Photon beam lines guide the light to the instruments in the experimental hall. The components are distributed along an essentially linear geometry of 3.4 km length, starting on the DESY campus in the northwest part of the city of Hamburg, and ending in the neighboring Federal State of Schleswig-Holstein, south of the city of Schenefeld, where the experimental hall is located. In the initial configuration the user facility has 3 SASE FEL and two spontaneous radiation undulator beam lines with in total 10 experimental stations. The site layout permits a later extension of the facility by another 5 beam lines.

Figure 1. Schematic layout of the XFEL facility.

The XFEL has a strong link to the running FLASH linear accelerator of the TESLA test facility (TTF) at DESY, which in nearly all respects truly is a pilot facility for this future project [5]. It comprises the necessary accelerator technologies, FEL process and photon beam lines. As a running user facility it provides lots of experience with FEL operation for user experiments. For many of the vacuum components and procedures needed for the XFEL up to 10 years operational experience exists [6]. In addition FLASH also is an ideal test bed for technical developments specifically required for the XFEL.
2. XFEL Vacuum System
The beam vacuum system of this facility contains sections operated at room temperature as well as at 2 K in the areas of the superconducting accelerating structures. Accordingly, the requirements, technical challenges and solutions for the various sections are quite different.

2.1. Vacuum Requirements
The beam vacuum system itself has to be made such as to avoid any effects causing significant beam losses or deterioration of the beam quality. In contrast to storage ring type light sources, here the beam particles pass the straight accelerator only once. Therefore the pressure requirements with respect to losses due to scattering on the residual gas are relaxed, and an average pressure of $10^{-7}$ mbar is acceptable. Effects like emittance growth, fast ion instabilities or dynamic pressure increase due to synchrotron radiation are negligible.

Deterioration of the beam quality by RF losses however is an issue due to the very short and intense bunches. Thus proper shielding of bellows, pump ports, gate valves etc. are necessary in most parts of the system. Within the undulator sections, where the diameter of the beam pipe will be quite narrow, challenging demands are put onto the surface quality of the vacuum chamber as described in more detail in section 4.3. However, using smooth tapers when changing the cross section usually will not help, as the angle has to be smaller than 3° due to the ultra short bunches. Eventually small steps are even better.

The vacuum system also needs to avoid effects causing deterioration of the superconducting cavity performance. Particles can act as field emitters and thus limit the performance of the cavities. Therefore any kind of particles must be avoided for operating the cavities at high accelerating gradients. The cavities are cleaned and finally assembled in clean rooms under conditions similar to the semiconductor industry. Although the cavities are forming the major part of the cold beam pipe itself, the remaining vacuum needs to preserve the particle cleanliness of the superconducting cavity surfaces by applying similar cleaning procedures to the vacuum components of the cold system. In addition, strong gas condensation from neighboring room temperature sections needs to be avoided onto the cold surfaces requiring a pressure level of $10^{-10}$ mbar in those areas. This will be accomplished using titanium sublimation pumps in combination with sputter ion pumps for part of the facility. Fast shutters next to the cold sections should protect the sensitive parts in case of a sudden vacuum break in the room temperature sections.

2.2. Cleaning and Installation
Following standard UHV-cleaning procedures the preparation of all vacuum components for the 1.6 km long main linac includes cleaning steps in a special clean room containing various facilities to remove particles [7], and installing them into the accelerator in local clean rooms. Components for the photon beam lines will be treated similarly to avoid contamination of e.g. mirrors with dust particles. Oil free pump stations [8] will be used for initial pump down. In addition, special automated procedures have been developed for pump down and venting to avoid any particle transport inside the beam pipe into critical areas during these processes.

3. Superconducting Linear Accelerator
The layout of the superconducting linac is very similar to the existing one at FLASH. The CAD model in figure 2 shows the three vacuum systems involved: The beam vacuum system operated at 2 K, the vacuum to insulate the cold components against ambient air and the room temperature vacuum system of the high power couplers.

For the beam vacuum system eight cavities, a superconducting magnet and a beam position monitor are grouped into 12 m long strings, which is closed off by manual valves at both ends as shown in figure 3. These strings are cleaned and assembled in a class 10 clean room. Thereafter the strings are assembled to the cold mass and finally inserted into the large insulating vacuum tank of a module. In-between two modules short interconnections including a higher order mode absorber [9]
and a pump port will be installed. Continuous pumping of the beam vacuum will be done by sputter ion pumps at a distance of 140 m with the system at room temperature, while the pumps mainly act as pressure sensors when being cold. At these locations it is planned to install automatic gate valves presently under development, which could be operated at room temperature and 2 K, and staying leak tight during temperature cycles of the system. This should allow separating the cold system in case of a dramatic failure into shorter sections during warm up, and thus prevent distribution of harmful gases and particles over the whole length of the superconducting linac.

Figure 2. CAD model showing the three vacuum systems of the superconducting linac.

Figure 3. 12 m long cavity string with 8 cavities, superconducting magnet, beam position monitor and manual valves as well as intermediate piece.

The high power couplers at each cavity have two ceramic windows, one at a temperature of 70 K and one at room temperature. This design enables the cavity to be closed off completely by mounting the coupler up to the first window during string assembly in the clean room. A common pump line connects the eight couplers of each module. Using a titanium sublimation and sputter ion pump a pressure of $10^{-10}$ mbar is usually reached during operation of the cavities.

The pressure needs for the insulating vacuum are relaxed; about $10^{-3}$ mbar are required before cooldown. This is achieved using roughing and turbomolecular pumps, although pump down times might be quite long due to the large amount of components and surfaces installed into the insulating vacuum tank.

It is planned to do a full performance test of all 116 modules in a special test facility at DESY. In addition, an RF-test of the more than 950 superconducting cavities will be performed in this facility, thus requiring appropriate vacuum installations. In contrast to the present layout of the FLASH tunnel the modules will be fixed to the ceiling of the XFEL tunnel.

4. Warm Vacuum System

4.1. Injector and Bunch Compressors

The laser driven RF source for the electrons uses a water-cooled brazed copper cavity as shown in figure 4. Complex diagnostic sections alternate with beam acceleration and beam formation.

Shortening of the electron bunches occur within the magnetic chicanes of the two bunch compressors, having a total length of 160 m. Here quite wide but flat vacuum chambers are required inside the deflecting magnets. Following the experience from FLASH copper coated stainless steel chambers are foreseen to fulfil the requirements with respect to the tight tolerances and minimizing RF losses. Alternatively, a movable chicane is presently investigated. Whether the fixation of the bypass section, which is located underneath a 700 mm diameter cryogenic bypass line about 2 m above floor level, will be done to the ceiling or the floor is not yet decided.

4.2. Collimation and Beam Distribution

Once the electrons are accelerated to full energy, they are guided through a 200 m long section to collimate and then distribute them into the two undulator beam lines. Special collimators should
protect the radiation sensitive undulator magnets against direct beam hits from mis-steered beams. Due to the short bunch distance within a bunch train, several bunches will already be on its way to the undulators once a problem is detected and the electron gun switched off. In addition, the collimators have to absorb losses from beam halo and dark current generated by the superconducting cavities. The collimator design follows the experience from FLASH using massive titanium blocks, which could withstand beam hits for a few bunches, brazed to water cooled copper blocks.

The 30 vacuum chambers for the fast kicker magnets for beam distribution will be made out of ceramics with sputtered metallic coating to reduce RF losses.

4.3. Undulators
The undulators will fill about 700 m build up in a modular structure. 5 m long undulators with 10 mm gap height will alternate with 1.1 m long intersections, containing a quadrupole magnet, phase shifter, beam position monitor, small absorber and a 20 l/s sputter ion pump as shown in figure 5. Without active pumping inside the undulator an average pressure of a few times $10^{-7}$ mbar is expected, assuming a conservative outgassing rate of $10^{11}$ mbar l/s cm$^2$.

The undulator vacuum chambers will pose challenges with respect to fabrication and surface preparation. Due to their small cross section and its long length losses by wake fields could be quite significant. Therefore losses in addition to the resistive effects from the chamber material itself should be kept at a level of 20%. Choosing aluminum a surface roughness with RMS values below 300 nm in longitudinal direction and an oxide layer thickness below 5 nm are required [10].

Made from extruded aluminum, the chamber has a cross section of 8.8 mm x 15 mm with two channels on each side for water cooling and Cerenkov fibers to continuously monitor radiation losses. A development program is ongoing for fabrication techniques, passivating coatings using Au, and cleaning procedures to ensure that the chambers are as smooth and oxide-free as possible. Details of part of the surface investigations are presented in [11].

4.4. Transport Beam Lines and Beam Dumps
About 1.7 km of transport beam lines in-between the various undulators and from there to the beam dumps will be needed. Here a cost effective solution is required, which offers sufficient electrical conductivity to minimize losses by resistive wake field effects over the long length of the system. It is planned to use copper tubes connected to stainless steel conflate flanges via inductive brazing, i.e. brazing under Ar atmosphere using locally the magnetic field of a strong coil to heat up the material. The detailed cleaning and storage procedure of these chambers still need to be worked out in order to keep the oxidation to a minimum. Pumping of these sections will be done using lumped sputter ion pumps of 60 l/s at several meter distances.
Once the electrons complete their path through the facility, they must be disposed of safely by removing them from the beam vacuum system and delivering them to quite massive beam dumps, where their kinetic energy is absorbed. In total 6 beam dumps are foreseen at various locations of the facility in order to allow successive commissioning and to serve all beam lines. At these locations exit windows are required as barriers to the vacuum system. These windows need to withstand the passage of the short and very intense electron bunches, resulting locally in high thermal and mechanical stress. Graphite seems to be a good candidate to fulfill these requirements; however its porous structure will not act as vacuum barrier. Therefore studies are ongoing to coat the graphite using thin brazing foils. In addition this foil should be polished in order to be used as mirror for an optical transition radiation detector to monitor online the position of the electron beam on the exit window.

5. Conclusions
The European X-ray free electron laser XFEL project recently has been approved. Among the various ambitious technologies involved, several technical challenges for the vacuum system need to be solved. For many components, especially for the superconducting linear accelerator, the injector and the bunch compressors one will profit from the solutions developed for FLASH and the long term experience with this facility. In addition, new developments are necessary, e.g. for a gate valve to be operated at very low temperatures and a new higher order mode absorber made out of special ceramics. Especially challenging are the undulator vacuum chambers with ambitious surface qualities and the exit windows to the beam dumps.

Following the XFEL project approval, the next steps for the vacuum system will be preparation of the ordering of the vacuum components for the superconducting linear accelerator as well as working out the detailed layout of the warm vacuum sections.

References
[1] Brinkmann R et al. (eds.) 2002 TESLA XFEL Technical Design Report - Supplement DESY-2002-167
Brinkmann R 2006 Proc. 28th FEL conf. (Berlin) http://www.bessy.de/fel2006/proceedings
Decking W 2007 Developments at the european X-ray free electron laser this conference ADV02-IS2
[2] Bozek J 2007 LCLS design, construction status, and first experiments this conference ADV03-IS2
[3] Shintake T 2007 Spring-8 x-ray free electron laser project, this conference ADV03-IS1
[4] XFEL Technical Design Report 2006 DESY-2006-097 http://xfel.desy.de
[5] Weise H 2006 The TTF/VUV-FEL (FLASH) as the prototype for the European XFEL project Proc. Linear Acc. Conf. (Knoxville) http://accelconf.web.cern.ch/accelconf/
[6] Zapfe K 2004 Vacuum 73 213
[7] Hahn U, Hesse M, Remde H and Zapfe K 2004 Vacuum 73 231
Zapfe K, Hahn U, Hesse M and Remde H 2003 A cleaning facility to prepare particle free UHV-components Proc. 11th Workshop on RF Superconductivity (Travemünde) http://srft2003.desy.de/fap/
[8] Böhnert M, Hensler O, Hoppe D and Zapfe K 2001 Oil-free pump stations for pumping of the superconducting cavities of the TESLA test facility Proc. of the 10th Workshop on RF Superconductivity (Tsukuba) KEK Proc. 2003-2 p. 477, http://conference.kek.jp/srf2001/
[9] Mildner N, Dohlus M, Sekutowicz J and Zapfe K 2005 A beam line HOM absorber for the European XFEL linac Proc. 12th Workshop on RF Superconductivity (Ithaca) http://www.lepp.cornell.edu/public/SRF2005/Proceedings.html
[10] Dohlus M (2006) DESY private communication
[11] Leandersson M, Westerberg L, Wohlenberg T, Zapfe K, Jensen J, Linnarsson M and Karlsson U 2007 Experimental analysis of the prototype undulator vacuum chamber for the European XFEL project this conference VST04-Or5